ANWG Report

1. *Introduction*
    1. *Brief into to Atmos neutrinos capabilities*
2. *Tools for Sensitivity Studies*
3. *Toy Example Results*
4. *Help Wanted - TASK LIST*

Thanks to contributors to the group discussions: Bonnie Fleming, Jeff de Jong, Ed Kearns, Tony Mann, Mark Messier, Jen Raaf, Mayly Sanchez, Joshua Spitz, Bob Svoboda, Jim Strait

PWG Report

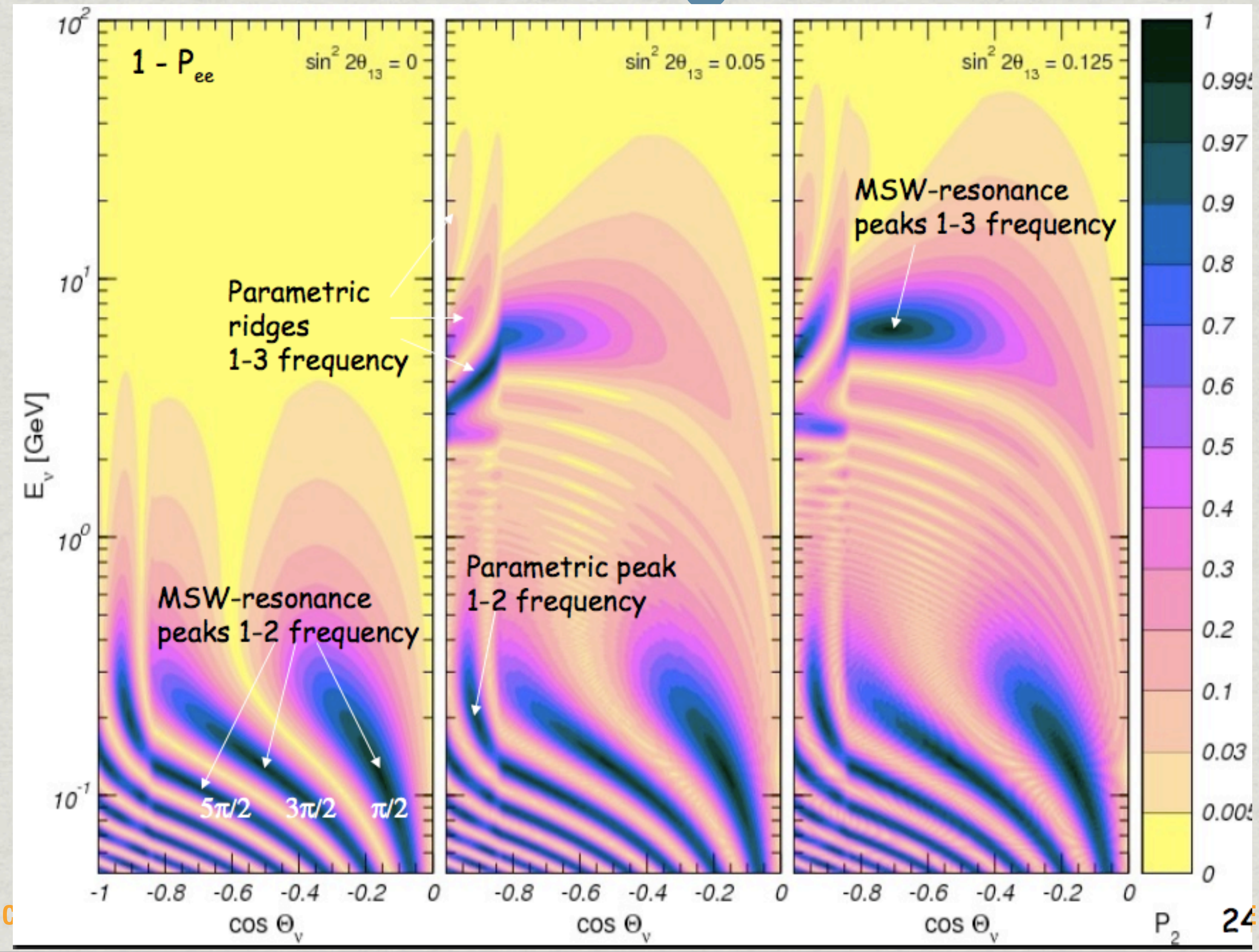
Unfortunately, I failed to provide the kind of detailed, useful information we were hoping for the Draft Physics Report as the sensitivity studies for LAr had not been completed.

Statements regarding WC detector sensitivity were based on sensitivities produced by SuperK/HyperK proponents in previous documents.

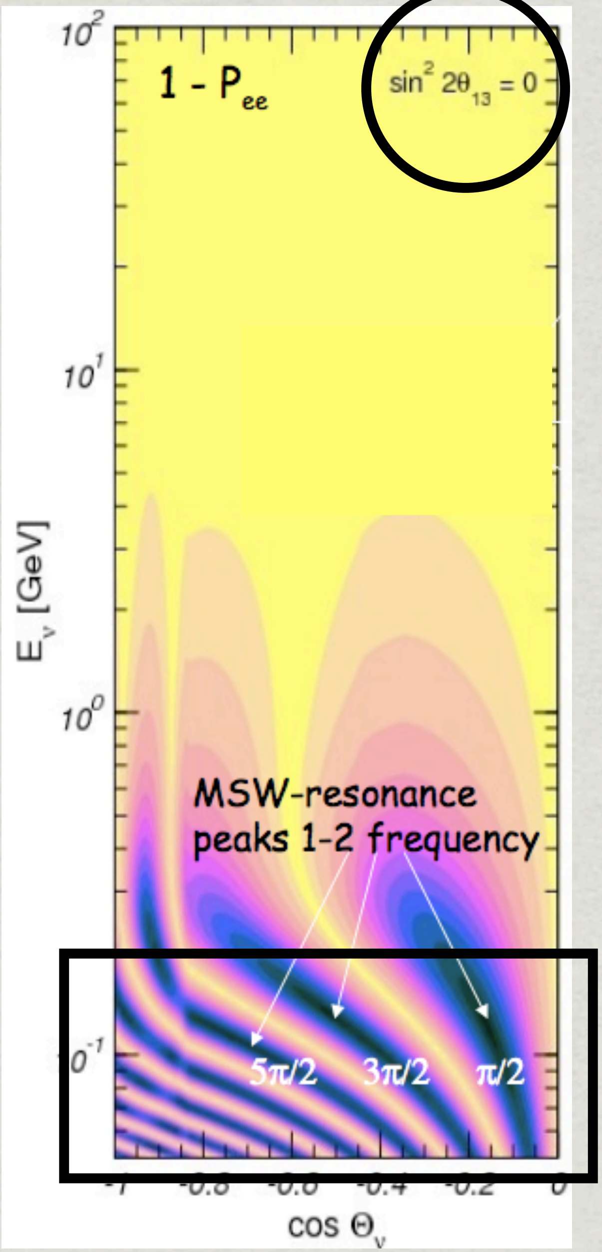
- Finish validation and testing of sensitivity tools.
- Provide LAr sensitivities
- Examine sensitivity of sensitivities to assumptions - identify key assumptions about LAr performance.
- Attempt to model WC detector analyses based on published SuperK information

A. Yu. Smirnov
"Atmospheric Neutrinos and Large Future Detectors", DDRD-doc-1002

Oscillograms



A. Yu. Smirnov
"Atmospheric Neutrinos and Large Future Detectors", DDRD-doc-1002



Solar Mass Scale Oscillations

solar scale

$$P(\nu_e \rightarrow \nu_\mu) = \cos^2(\theta_{23}) P(\nu_e \rightarrow \nu_x)$$

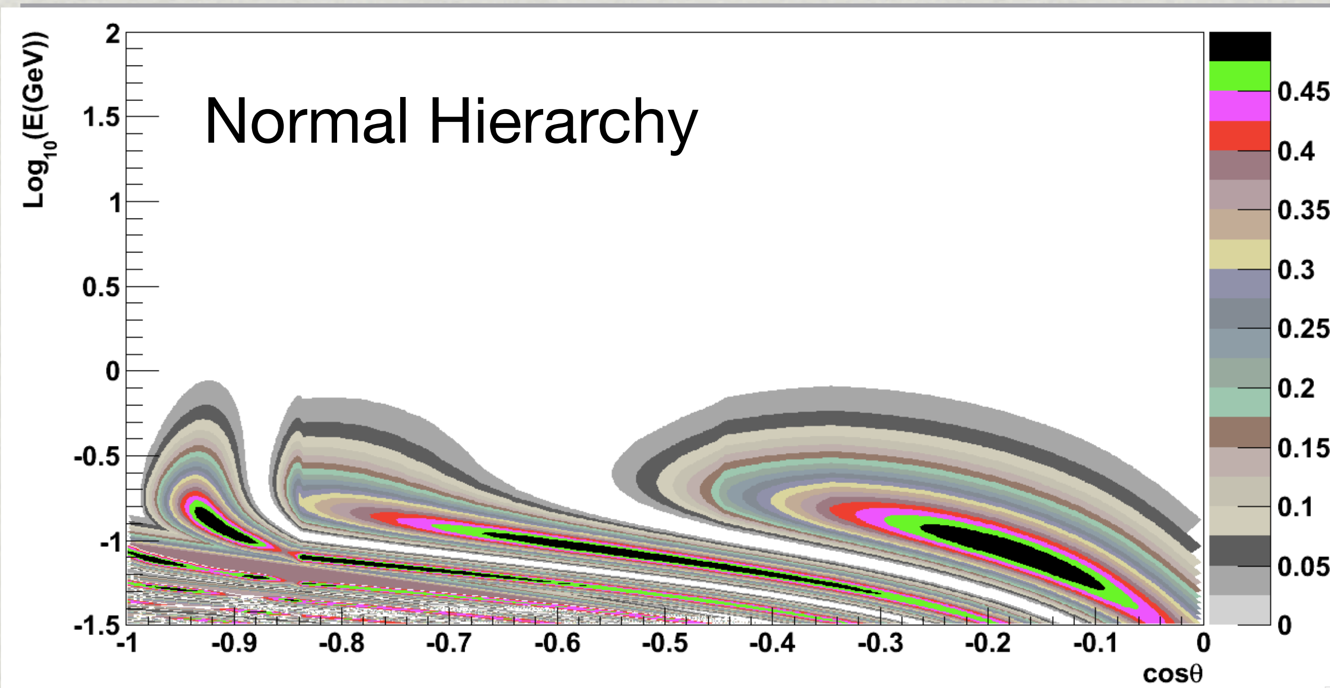
Sensitivity to the octant of θ_{23}.

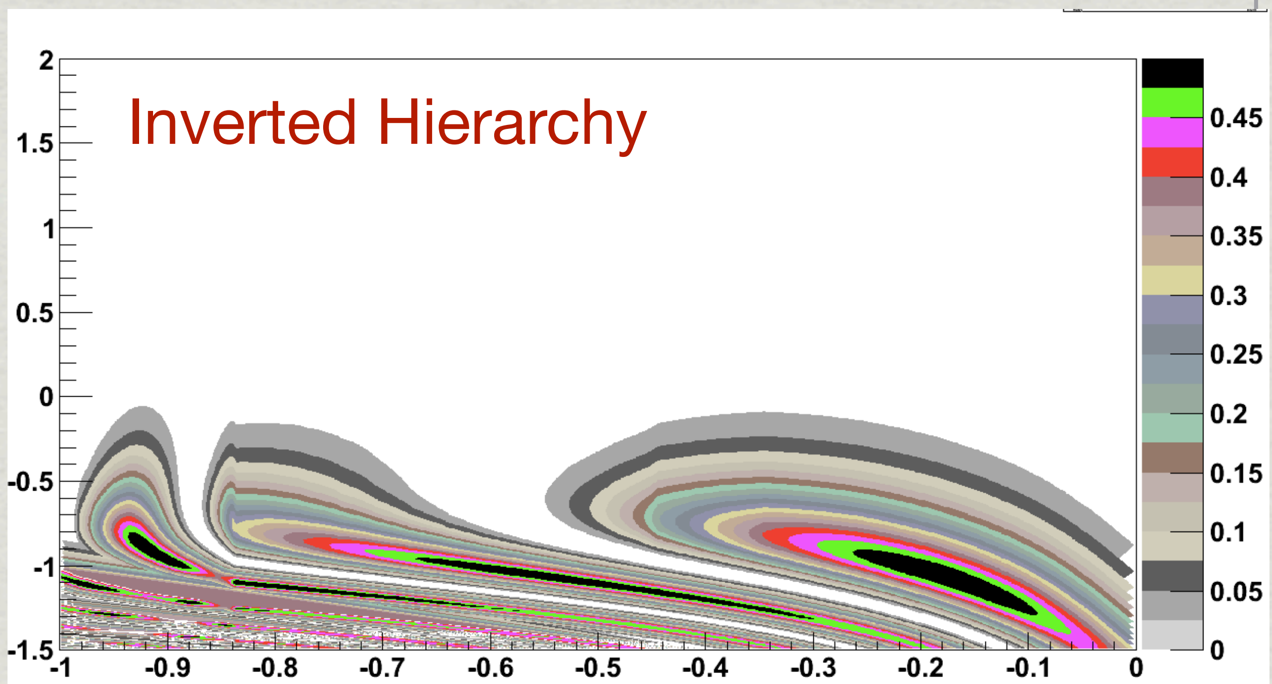
Octant sensitivity even if θ_{13} is small or zero.

Unfortunately effect is 'screened' by initial flavor ratio.

Signature: changes in the flavor composition of low energy, upgoing events.

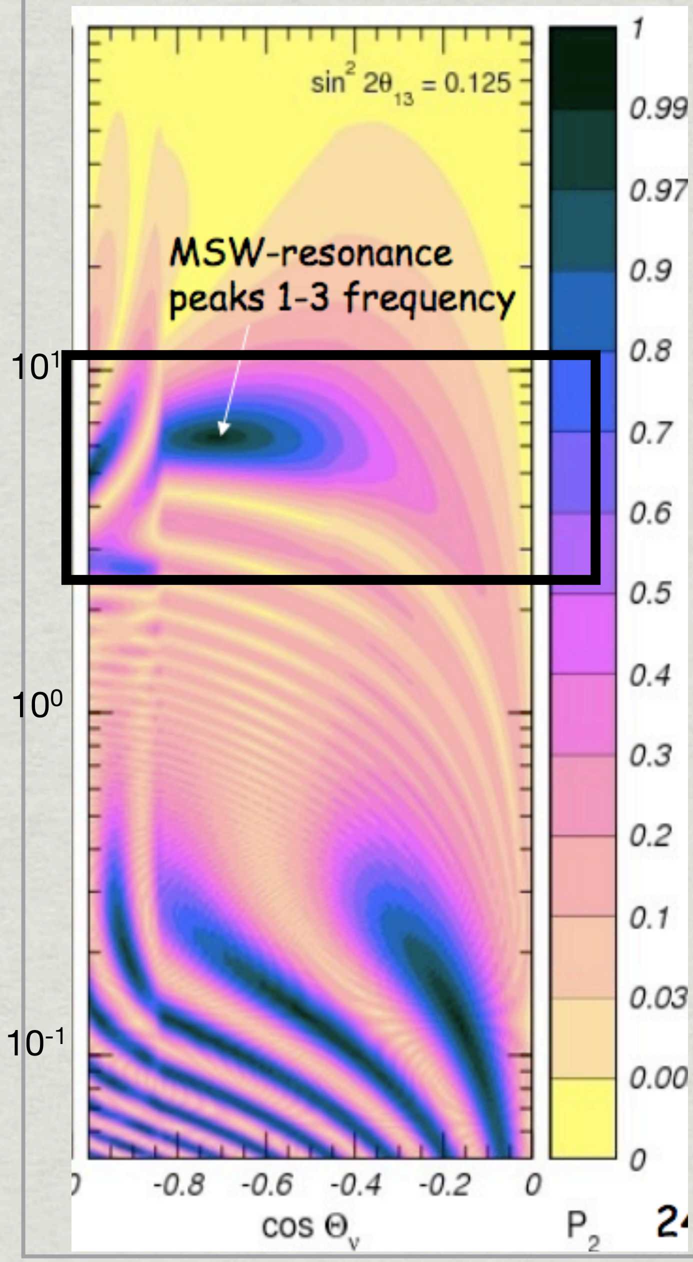
$P(\nu_\mu \rightarrow \nu_e)$





$\theta_{12}=32.3$
$\theta_{23}=45.0$
$\theta_{13}=0$
$\Delta m^2_{23}=2\times10^{-3}\ eV^2$
$\Delta m^2_{12}=5\times10^{-5}\ eV^2$

A. Yu. Smirnov
"Atmospheric Neutrinos and Large Future Detectors", DDRD-doc-1002



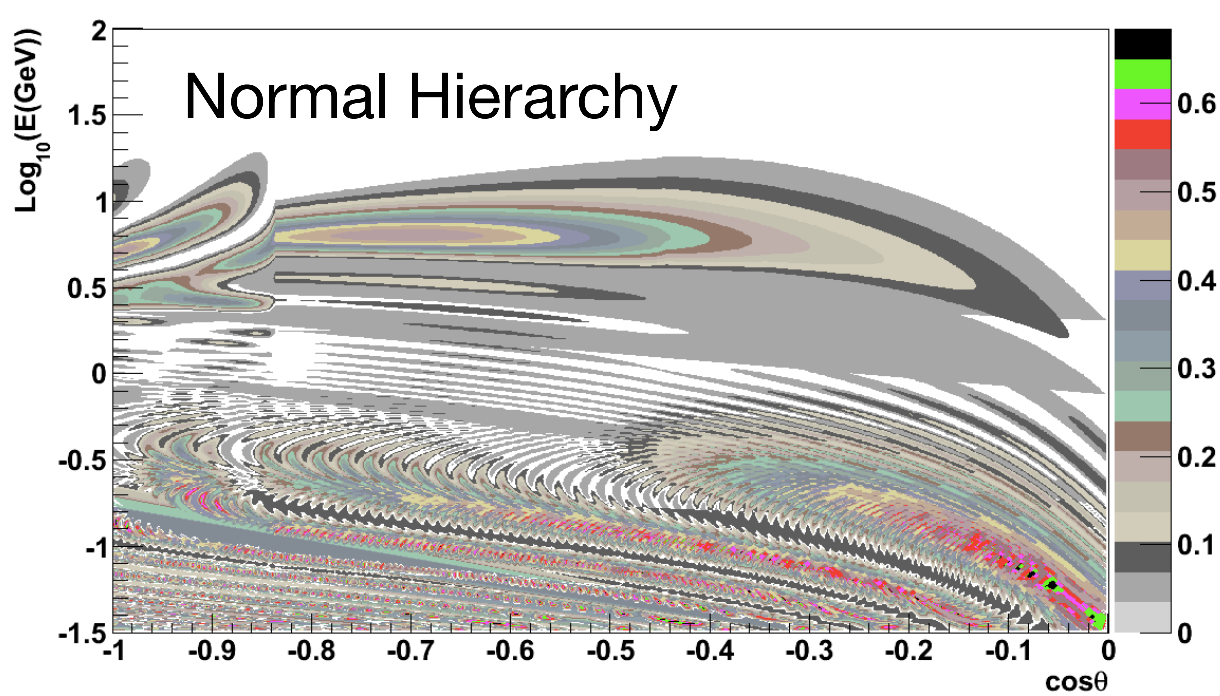
θ_{13} and hierarchy

non-zero θ_{13}

Signature: Changes in flavor composition of 1-10 GeV upgoing neutrino events.

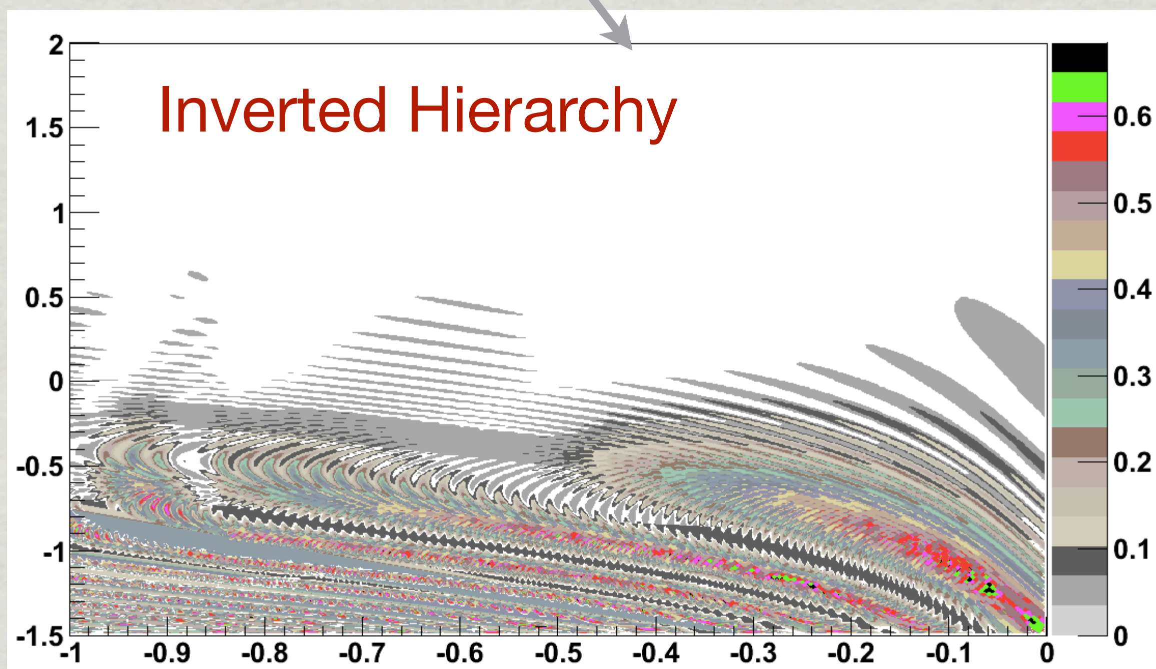
hierarchy: Driven by matter effects, sign changes for inverted hierarchy

Signature: Differences in flavor composition of 1-10 GeV upgoing (anti) events.



$P(\nu_\mu \rightarrow \nu_e)$

Reversed for
Anti-neutrinos



θ_{12}=32.3
θ_{23}=45.0
θ_{13}=10.
$\Delta m^2_{23}=2.4\times10^{-3}$ eV^2
$\Delta m^2_{12}=7.59\times10^{-5}$ eV^2

Mass Hierarchy

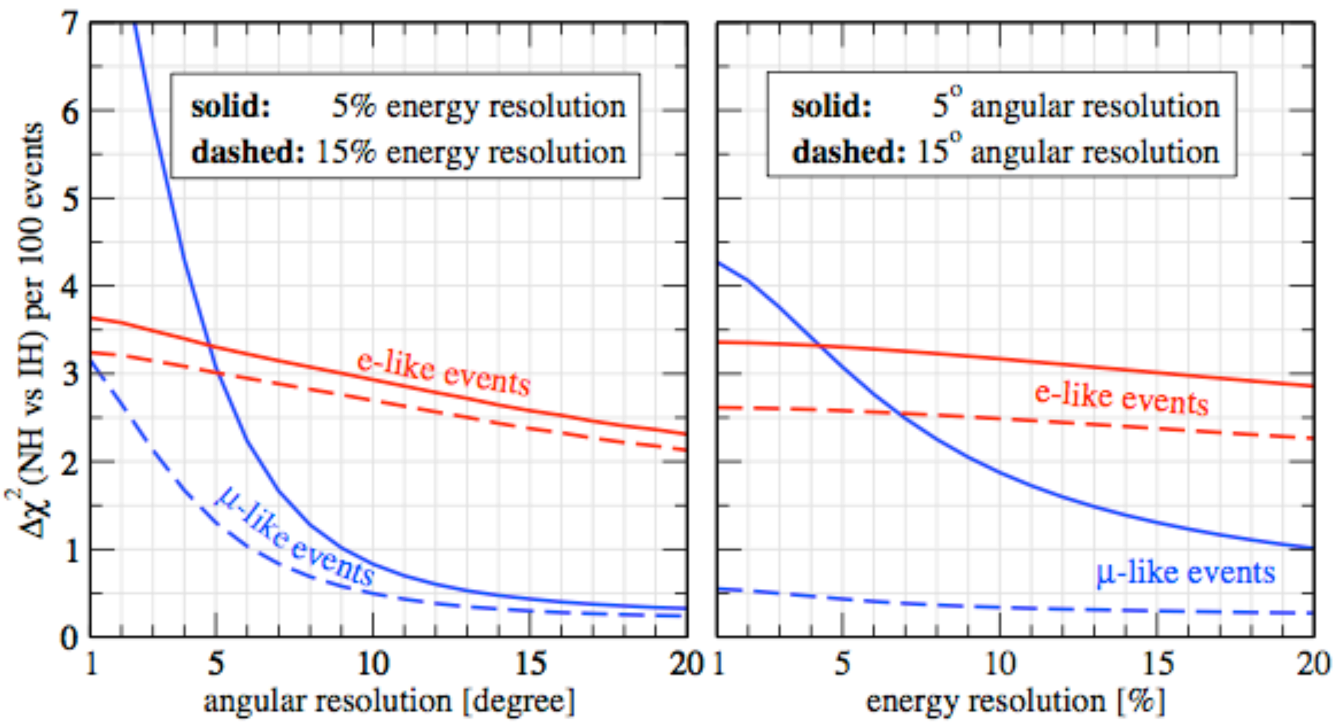


Figure 2: $\Delta\chi^2$ between NH and IH per 100 events as defined in Eq. (33) as a function of the angular resolution (left) and energy resolution (right). The oscillation parameters are fixed to $\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $|\Delta m^2| = 2.4 \times 10^{-3}$ eV^2, and we use 20×20 bins in the intervals 2 GeV $\leq E_\nu \leq$ 10 GeV and $0.1 \leq \cos\theta_n \leq 1$, statistical errors only, and 100% charge identification.

"Determining the Neutrino Mass Hierarchy with Atmospheric Neutrinos", Petcov and Schwetz, hep-ph/0511277.

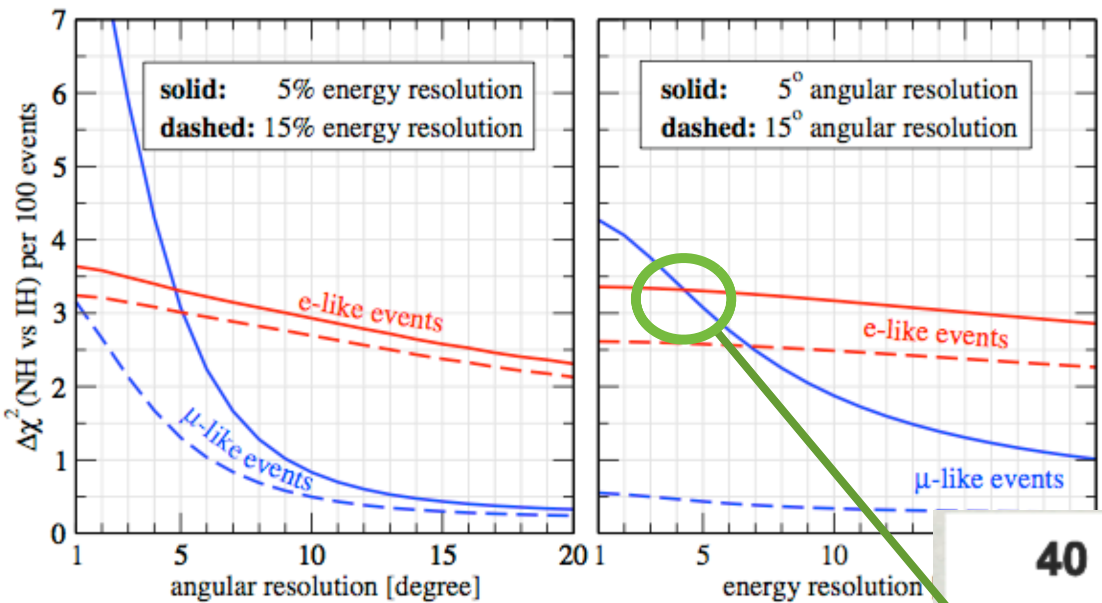
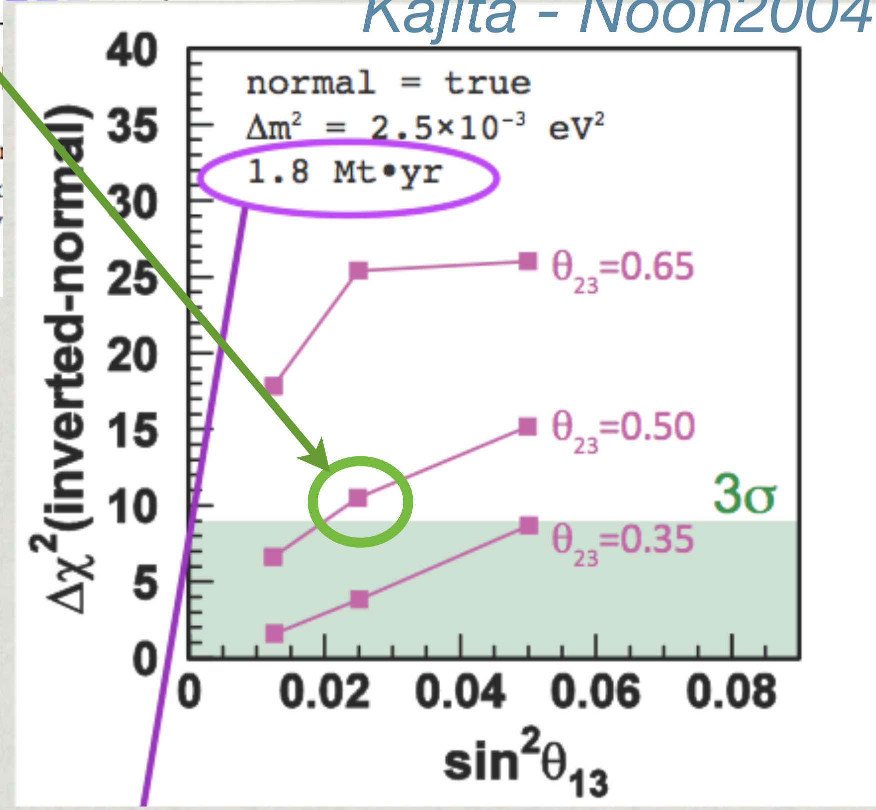


Figure 2: $\Delta\chi^2$ between NH and IH per 100 events as defined in Eq. (33) as a fu[n]
resolution (left) and energy resolution (right). The oscillation parameters are fixe[d]
$\sin^2\theta_{23} = 0.5$, $|\Delta m^2| = 2.4 \times 10^{-3}$ eV^2, and we use 20×20 bins in the intervals 2 GeV
$0.1 \leq \cos\theta_n \leq 1$, statistical errors only, and 100% charge identification.

"Determining the Neutrino Mass Hierarchy with Atmospheric Neutrinos", Petcov and Schwetz, hep-ph/0511277.

Kajita - Noon2004



1. *LAr can have an improved sensitivity compared to WC.*
2. *LAr can have a **much improved** sensitivity compared to WC.*
3. *LAr sensitivity depends strongly on resolution.*

Sensitivity Studies

Full simulation

Files generated in quanta
of 10 kton-yrs.
Two types:
$\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$, no oscillations
All mu-> tau neutrinos
For each of H_20, LAr

GENIE with atmos nu flux drivers

Detector Performance Assumptions (DPAs)

Reconstruction (AtNuReco)

AtNuEvent objects

Binning (AtNuBinner)

AtNuMini objects

Oscillation probabilities for input PMNS values, neutrino (type, E, cos θ)

AtNuAnalysis

Plots

Simulation Programs

Standard tools like GLoBES don't work for atmospheric neutrinos. Goal was to develop tools that are fast and allow us to simulate the analysis of atmos neutrino samples with as much realism as possible. Start with large event-generator level samples produced with GENIE and the BGLRS or FLUKA atmospheric neutrino fluxes (FLUKA here):

Event Categorization:

Containment Categories (FC,PC)

Flavor Categories (e-like, mu-like, NC-like)

Topology Categories (single/multi ring, QE/nonQE-like)

Other Categories (sub/multi GeV, nu/nubar-like)

AtNuReco:
Driven by a reco 'scheme'-string at command line

Event Measurement:

Energy, zenith angle

AtNuBinner:
Driven by a binning 'scheme'-string at command line

Event Binning:

Each would be done differently - binning in (E,zenith), L/E, energy cuts?

Physics Analysis:

Exists: Hierarchy, θ_{13}*, octant of* θ_{23}

AtNuAnalysis:
Driven by a binning 'scheme' - string at command line

Example Plots

In terms of getting the simulation machinery validated, we have been trying to compare to other published studies and limiting cases. *More work is needed here before I will be completely comfortable with the outputs.*

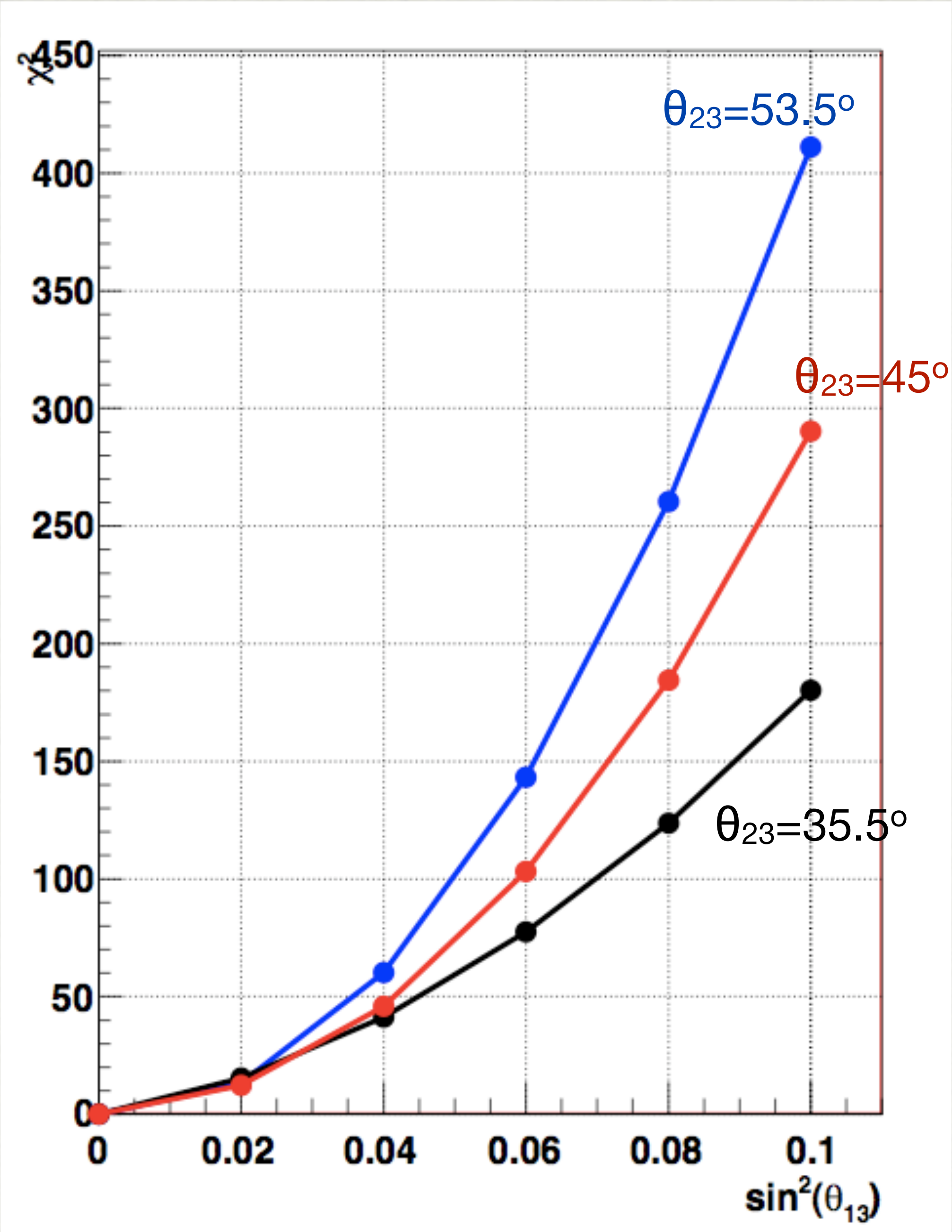
The following slides show examples for a (rather foolish) toy detector / binning scheme:

Perfect mu CC/ non-mu CC classification
Perfect E measurement (CC)

12 bins in energy
(100 MeV bins from 0.1-1.0 GeV, 1-2 GeV, 2-5 GeV, 5->infinity)

Foolish for many reasons:
perfect classification, energy reconstruction
non-optimum binning (no zenith angle, nu/nubar info)

θ_{13} Sensitivity



Foolish Detector / Analysis

Perfect mu CC/ non-mu CC classification:

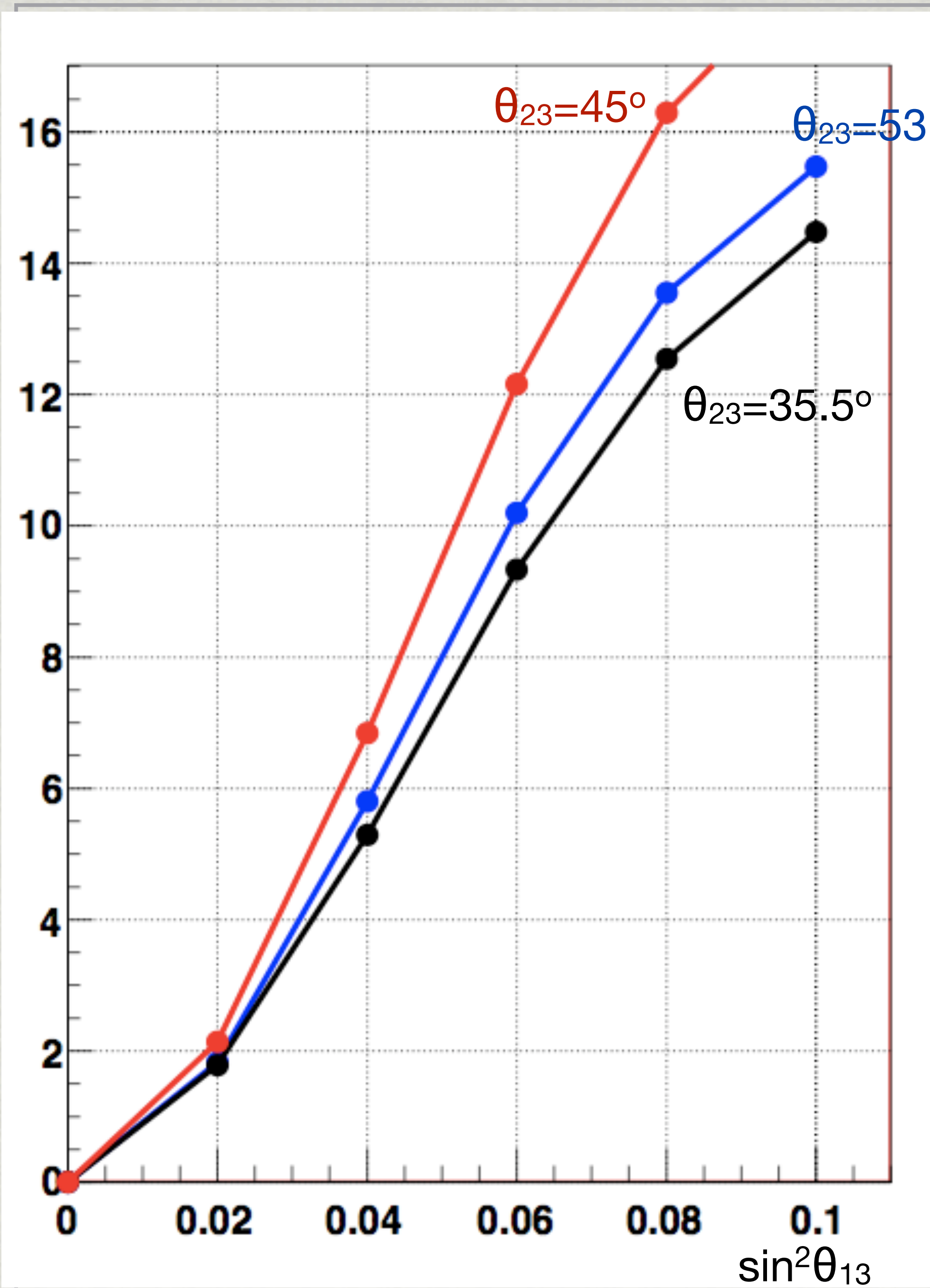
Perfect E measurement (CC)

12 bins in energy
(100 MeV bins from 0.1-1.0 GeV, 1-2 GeV, 2-5 GeV, 5->infinity)

NOT realistic for two reasons:
perfect classification
non-optimum binning

Table 8-25: Current values of parameters:

Parameter	Value/error	Source
Δm^2_{23}	$2.46\pm0.11 \times 10^{-3}$ eV^2	M.C. Gonzalez-Garcia et al. JHEP 1004:056,2010.
Δm^2_{12}	$7.59\pm0.20 \times 10^{-5}$ eV^2	
θ_{23}	42.8+4.7-2.9 °	
θ_{12}	34.4±1.0	
θ_{13}	5.6±3.0-2.7	



Hierarchy Sensitivity

Foolish detector / analysis

Perfect mu CC/ non-mu CC classification:

Perfect E measurement (CC)

12 bins in energy
(100 MeV bins from 0.1-1.0 GeV, 1-2 GeV, 2-5 GeV, 5->infinity)

NOT realistic for two reasons:
perfect classification
non-optimum binning

Table 8-25: Current values of parameters:

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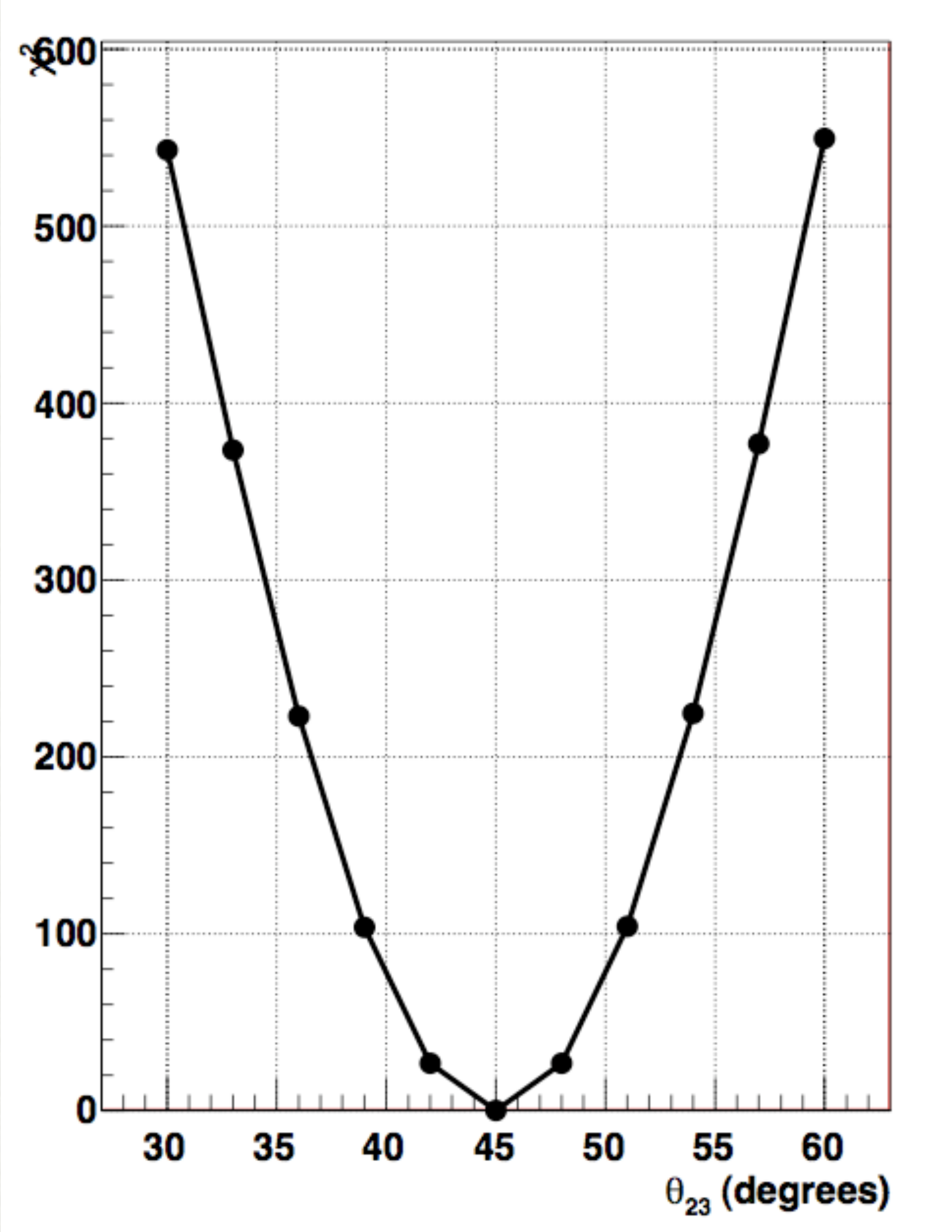
Δm^2_{23}	$2.46\pm0.11 \times 10^{-3}$ eV^2	M.C. Gonzalez-Garcia et al. JHEP 1004:056,2010.
Δm^2_{12}	$7.59\pm0.20 \times 10^{-5}$ eV^2	
θ_{23}	$42.8{+4.7}{-2.9}$ °	
θ_{12}	34.4 ± 1.0	
θ_{13}	$5.6{\pm3.0}{-2.7}$	

Set to zero for this plot

Small sensitivity to hierarchy even for θ_{13}=0!



Octant Sensitivity

Foolish Detector / Analysis

Perfect mu CC/ non-mu CC classification:

Perfect E measurement (CC)

12 bins in energy
(100 MeV bins from 0.1-1.0 GeV, 1-2 GeV, 2-5 GeV, 5->infinity)

NOT realistic for two reasons:
perfect classification
non-optimum binning

Table 8-25: Current values of parameters:

Parameter	Value/error	Source
Δm^2_{23}	$2.46 \pm 0.11 \times 10^{-3}$ eV^2	M.C. Gonzalez-Garcia et al. JHEP 1004:056,2010.
Δm^2_{12}	$7.59 \pm 0.20 \times 10^{-5}$ eV^2	
θ_{23}	42.8+4.7-2.9 °	
θ_{12}	34.4 ± 1.0	
θ_{13}	5.6±3.0-2.7	

Analysis Programs

One of my goals of this meeting was to hopefully find some volunteers to get involved at the level of running the sensitivity codes.   I am pleased to say that there were a few nibbles!

The package requires ROOT, GENIE, and Mark Messier's 3-flavor oscillation classes (PMNS and EarthModel).

Spoke with Brian Rebel yesterday about getting this installed on LBNE collaborator-accessible nodes here at Fermilab. You should hear more about that in a couple of weeks.

```
./atnureco -g atnufiles.xml -s PERFECT -e 510. -o FOOL.reco.root -A
./atnubinner -i FOOL.reco.root -s PERFECT -o FOOL.binned.root

./atnuanalysis -i FOOL.binned.root -s OCTANT -o FOOL-OCTANT.root
./atnuanalysis -i FOOL.root -s HIERARCHY -o FOOL-HIERARCHY.root
./atnuanalysis -i FOOL.root -s THETA13 -o FOOL-THETA13.root
```

2) What will be the impact ***on science*** of knowing the information to various levels of precision.

- Complete sensitivity studies to evaluate precision.
- How much does this add to the ***total*** sensitivity of LBNE?

4-fold Ambiguities:

- θ_{13}
- δ_{CP}
- Hierarchy
- octant of θ_{23}

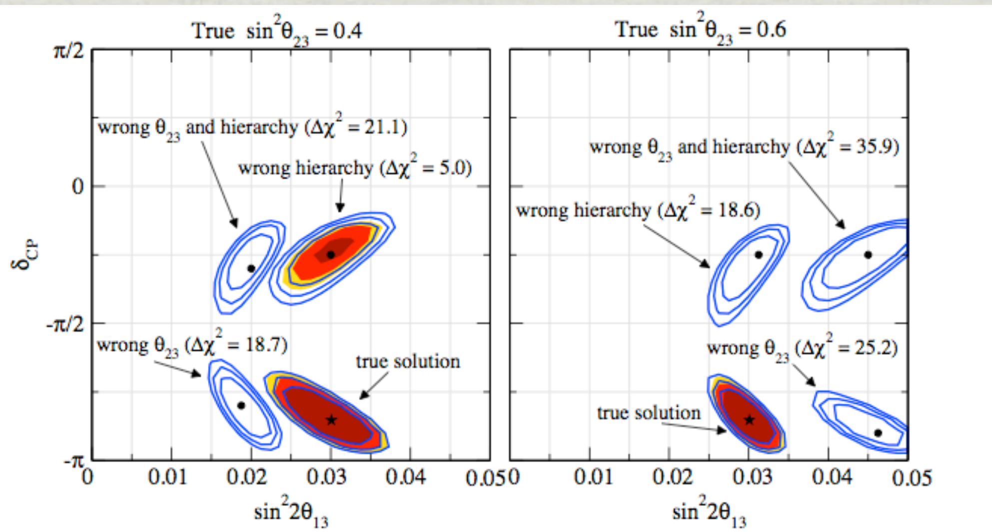


Figure 1: Allowed regions in the $(\sin^2 2\theta_{13}, \delta_{CP})$ plane at 2σ, 99%, and 3σ CL (2 dof) of the true and all degenerate solutions for $\sin^2 2\theta_{13}^{\rm true} = 0.03$, $\delta_{CP}^{\rm true} = -0.85\pi$, and $\sin^2\theta_{23}^{\rm true} = 0.4$ (left) and $\sin^2\theta_{23}^{\rm true} = 0.6$ (right). The solid curves correspond to LBL data only, and the shaded regions correspond to LBL+ATM data. The true best fit point is marked with a star, the best fit points of the degenerate solutions are marked with dots, and the corresponding $\Delta\chi^2$-values of LBL+ATM data are given in the figure. The true mass ordering is the normal hierarchy.

Huber et al, hep-ph/0501037 (2005)

Combined Octant Sensitivity

Octant Sensitivity from AtNu Measurement

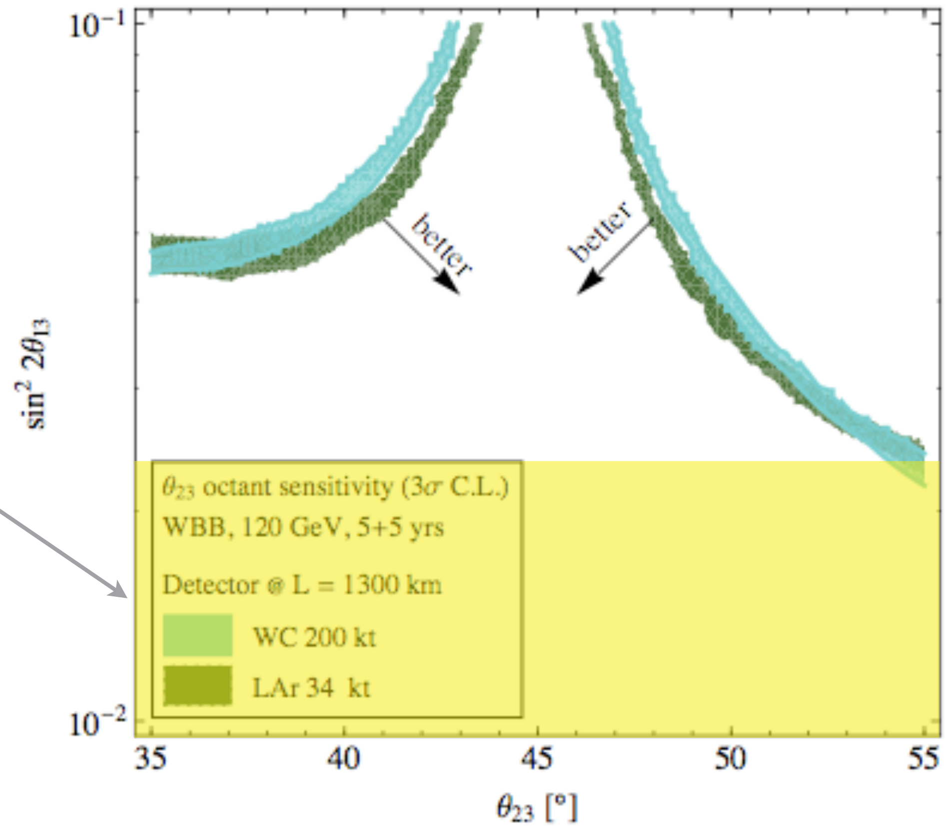


FIG. 29. Sensitivity of LBNE to resolve the θ_{23} octant degeneracy for 5+5 years of $\nu+\bar{\nu}$ running at 700 kW assuming the August 2010 beam design (red curve in Fig. 2) and normal mass hierarchy. The blue band shows the results for 200 kt WC and the green for 34 kt LAr. The width of the bands corresponds to the impact of different true values for δ_{CP}, ranging from a 10% to 90% fraction of δ_{CP}. In the region above the bands, the determination of the θ_{23} octant is possible at 3σ. Resolution of the octant degeneracy is determined by simulating data for some true value of θ_{23} and fitting with $\theta_{23}^{test} = \pi/2 - \theta_{23}^{true}$ (i.e., no marginalization over θ_{23}).

3) Expected state of knowledge of the topic from current and planned experiments in the next 5/10/15 years.

- Need to say something about INO.

  Thank you Brajesh Choudhary for putting me in touch with the appropriate INO people.

- Need to say something about MINOS

  Thank you Andy Blake for agreeing to provide something.

3) Identify primary backgrounds.

1. *Do the arguments re. cosmogenic backgrounds, depth, and shielding for proton decay detection really also hold for atmospheric neutrinos?*

2. *Sanity check based on scaling measured background in Soudan 2. (photons, neutrons/K_L)*

Based on feedback from EC and others, now a high priority item for us to think about.

4) Quantify the sensitivity to the science (as a function of running time) for the reference configurations based on performance parameters the detector WGs will provide.

- Complete sensitivity studies to evaluate precision for LAr (longer task list in a moment).

  Will be done with the 'bubble-chamber'-like reconstruction assumptions described at the last meeting - thanks to Tony Mann, Dave Cline and Bob Svoboda for information (bubble chamber-like reco in LAr and decay tagging).

  ..and the Kearns binning scheme developed yesterday.

- Basis for estimates of WC sensitivity - our calculations or published statements?

Help Wanted (1)

Tools:

1. *Running and validating the new generic Atmos Neutrino Driver Costas has added to GENIE.*
2. *Running / validating the simulations tools (AtNuReco, AtNuBinner, AtNuAnalysis).*
3. *Adding calculation of (Δm^2_{23}, $\sin^2(\theta_{23})$) measurement precision to AtNuAnalysis.*
4. *(Long Term) Adding calculation of exotic scenario sensitivity to AtNuAnalysis (CPTV, MaVN, LIV...).*
5. *(Long Term) Help package and publish this tool for the community.*
6. *(Long Term) Add systematic error treatment to analyses (structure was designed to support this).*
7. *(Long Term) How to handle events with a vertex in the rock? Up-stopping events and upward throughgoing muons. Is a calculation of the atmospheric-neutrino induced muon flux at our location sufficient?*

Help Wanted(2)

Sensitivity Studies:

1. *(LAr) Running the analysis programs to determine how LAr sensitivity varies as reconstruction/classification assumptions are changed. What are the key assumptions? What is our uncertainty on them?*
2. *(LAr) Running the analysis programs to determine how LAr sensitivity varies as the binning scheme is changed.*
3. *(LAr) - Help develop more realistic / sophisticated LAr reco and binning 'schemes'.*
4. *(LAr) - Determine the muon containment function for proposed geometries.*
5. *(WC) - Rather than rely on SuperK/HyperK studies, do we want to develop our own DPAs for WC? All the information is out there (in theses), and we know the answer we have to get (i.e. agree with SuperK results/HyperK statements).*

Help Wanted (3)

Combined sensitivity with LBL neutrinos:

1. *What is the best way to demonstrate the combined sensitivity (e.g. is there a key plot)?*
2. *How can we combine results from the working groups to determine the combined sensitivity?*

Help Wanted (4)

Other Experiments:

1. *Information about INO on 5/10/15 year timescales?*
2. *Information from MINOS on 5/10/15 year timescales?*

Backgrounds:

1. *Do the arguments re. cosmogenic backgrounds, depth, and shielding for proton decay detection really also hold for atmospheric neutrinos? Sanity check based on scaling measured background (photons and neutrons/K_L) in Soudan 2.*

BACKUP

To Do Items

1. Summarize the case for why we should do the measurement.

2. What will be the impact on science of knowing the information to various levels of precision.

3. Expected state of knowledge of the topic from current and planned experiments in the next 5/10/15 years.

4. Quantify the sensitivity to the science (as a function of running time) for the reference configurations based on performance parameters the detector WGs will provide.

5. Identify primary backgrounds.

6. Provide enough information for the collaboration to make an informed decision on detector technology statements for CD-1 report.

Working Group Charge

1. Summarize the case for why we should do the measurement.
2. What will be the impact on science of knowing the information to various levels of precision.
3. Expected state of knowledge of the topic from current and planned experiments in the next 5/10/15 years.
4. Quantify the sensitivity to the science (as a function of running time) for the reference configurations based on performance parameters the detector WGs will provide.
5. Identify primary backgrounds.
6. Provide enough information for the collaboration to make an informed decision on detector technology statements for CD-1 report.

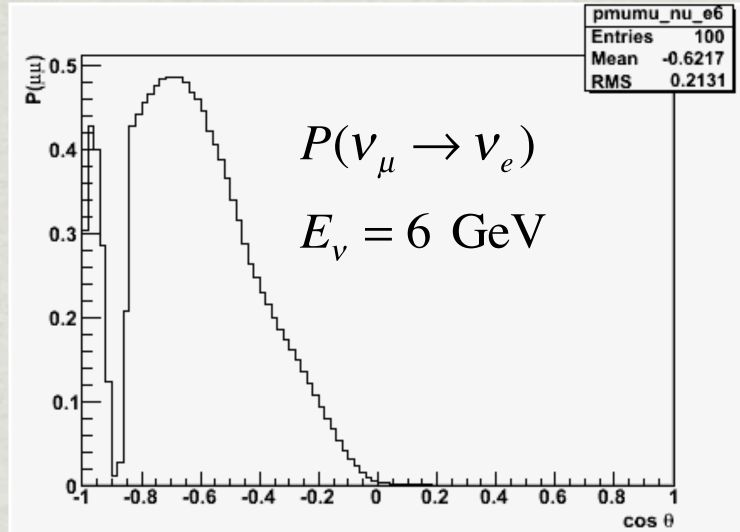
Oscillation Probabilties

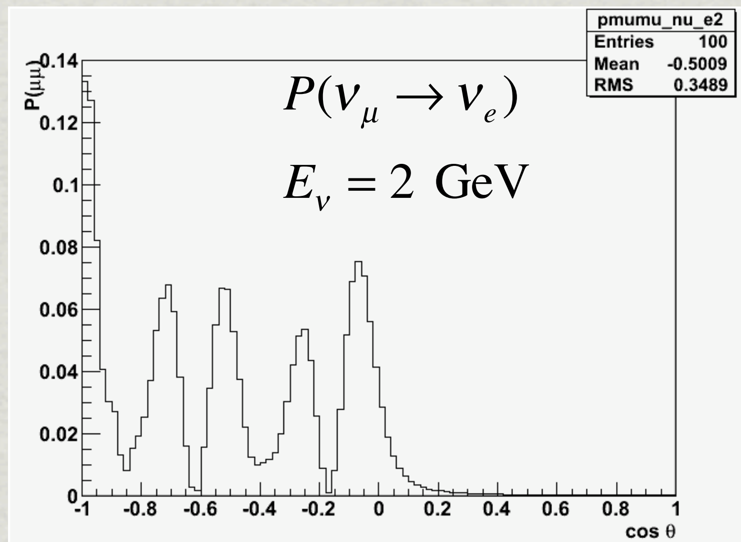
Code to calculate oscillation probabilities for input PMNS values, and neutrino information, has been provided by Mark Messier (Thanks!).

Classes to incorporate the earth model (PREM or Stacey) and the calculation of the oscillation probability.

Calculation is based on constant-density shells which agree with the selected model to a tolerance of 1%.

Calculation of oscillation probability: "Matter effects on three-neutrino oscillation", V. Barger et al., Phys. ReV. D22, 2718 (1980)





PMNS pmns(35.0*M_PI/180,45.0*M_PI/180.0,10.0*M_PI/180.0, 0.0,8.0E-5, 2.43E-3);

Zenith Angle Analysis

Data binned according to:

event type
+
momentum
+
zenith angle

420 bins for SK-I
420 bins for SK-II
420 bins for SK-III

Datasets	
SK-I FC/PC:	1489 days
SK-I Upmu:	1646 days
SK-II FC/PC:	798 days
SK-II Upmu:	828 days
SK-III FC/PC:	518 days
SK-III Upmu:	635 days

χ^2 fit in bins of zenith angle with systematic error pull terms:

$$\chi^2 = \sum_{i=1}^{N_{bins}} 2\left(N_i^{exp} - N_i^{obs} + N_i^{obs}\ln\frac{N_i^{obs}}{N_i^{exp}}\right) + \sum_{j=1}^{N_{sys}}\left(\frac{\varepsilon_j}{\sigma_j^{sys}}\right)^2$$

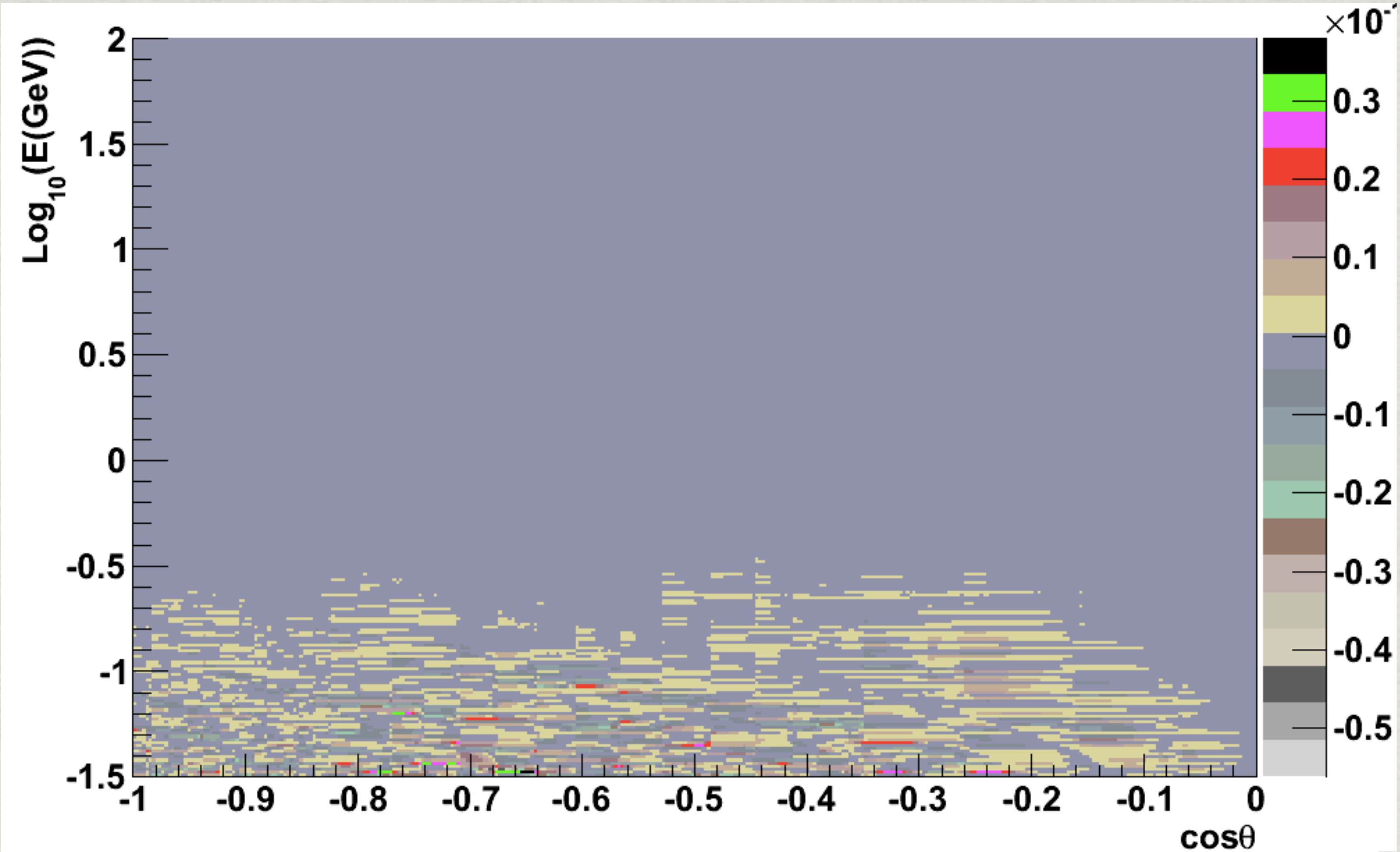
where $$N_i^{exp} = N_i^0 \cdot P\left(\nu_\alpha \to \nu_\beta\right)\left(1 + \sum_{j=1}^{N_{sys}} f_j^i \varepsilon_j\right)$$

122 systematic error terms to account for uncertainties in:

Neutrino flux | Cross sections
Event reconstruction | Data reduction

$P(\mu \rightarrow e)$ NH - $P(\mu \rightarrow e)$ IH

θ_{12}=32.3, θ_{23}=45.0, θ_{13}=0, $\Delta m^2_{23}=2\times10^{-3}$ eV^2, $\Delta m^2_{12}=5\times10^{-5}$ eV^2



A Perfect detector has sensitivity to hierarchy even if θ_{13}=0!

Water Cerenkov

A large amount of information is available about the performance of the SuperK detector for atmospheric neutrino studies.

Thanks to Jen Raaf and Ed Kearns for directing me to much of it, in particular the dissertations of:

- M. Ishitsuka (2004)
- R. Wendell (2008)
- Y. Takanega (2008)
- F. Dufour (2009)
- C. Ishihara (2010)

		Sub-GeV			Multi-GeV			PC
		1-ring e-like	1-ring μ-like	multi-ring μ-like	1-ring e-like	1-ring μ-like	multi-ring μ-like	
CC $\nu_e+\overline{\nu}_e$	Q.E.	69.4%	0.4%	0.8%	37.8%	0.1%	0.2%	0.3%
	single meson	14.4%	0.1%	1.6%	24.4%	0.1%	0.5%	0.4%
	multi π	2.4%	0.0%	1.2%	18.5%	0.2%	1.7%	1.2%
	coherent π	1.7%	0.0%	0.1%	2.1%	0.0%	0.0%	0.0%
	total	87.9%	0.5%	3.7%	82.8%	0.4%	2.4%	1.9%
CC $\nu_\mu+\overline{\nu}_\mu$	Q.E.	0.8%	73.4%	8.6%	0.9%	50.7%	4.1%	18.7%
	single meson	1.0%	16.6%	45.1%	1.1%	30.0%	30.5%	22.0%
	multi π	0.5%	2.5%	33.7%	4.8%	15.8%	58.7%	54.8%
	coherent π	0.1%	1.8%	3.1%	0.1%	2.9%	1.6%	1.7%
	total	2.4%	94.5%	90.5%	6.9%	99.4%	94.9%	97.2%
NC		9.7%	5.0%	5.8%	10.3%	0.2%	2.7%	0.9%

Table 6.2: Fraction of each neutrino interaction mode in FC and PC atmospheric neutrino Monte Carlo events.

M. Ishitsuka

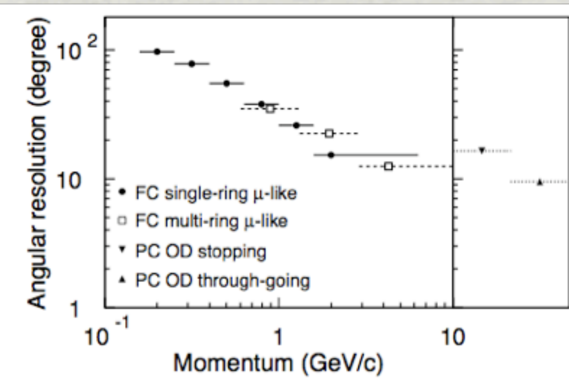
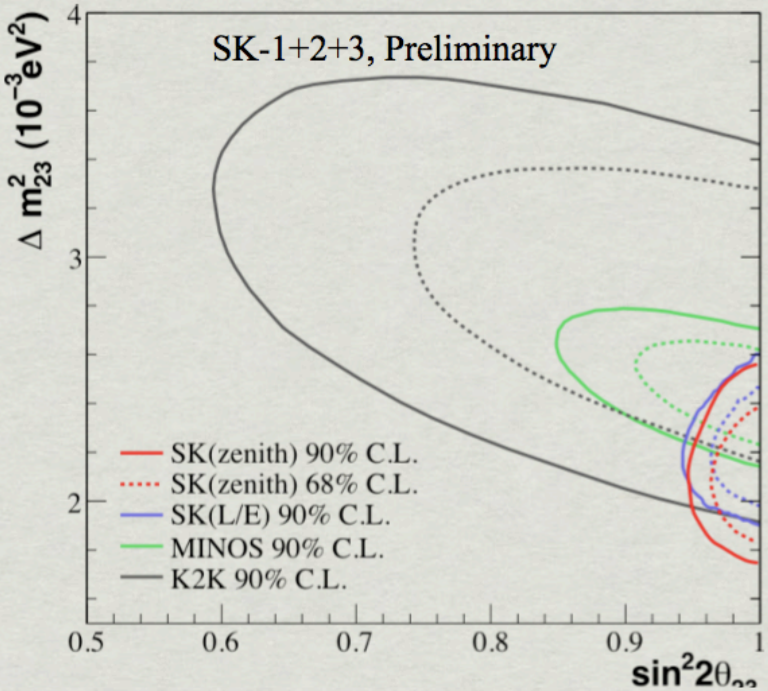


Figure 8.13: Angular resolution of neutrino direction for each sample as a function of the lepton momentum for FC single-ring events and E_{vis2} for FC multi-ring events.



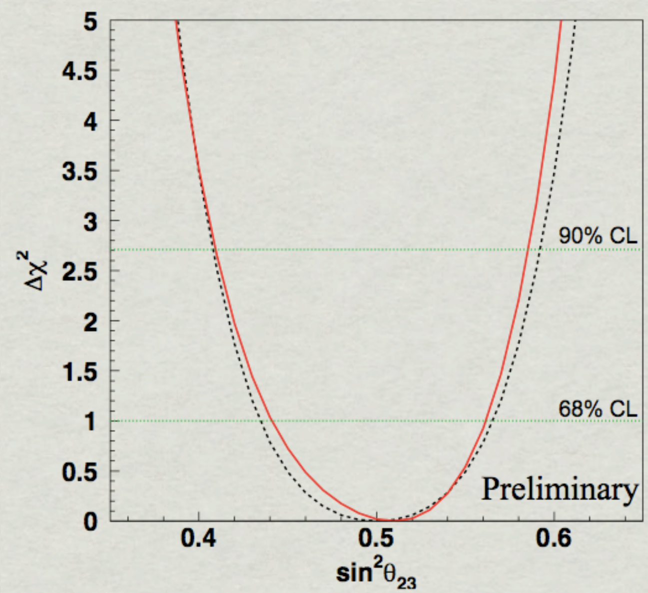
Zenith angle analysis best fit

$$
\begin{aligned}
\sin^2 2\theta_{23} &= 1.0 \\
\Delta m^2_{23} &= 2.1 \times 10^{-3} eV^2 \\
\chi^2/d.o.f. &= 468/420
\end{aligned}
$$

L/E analysis best fit

$$
\begin{aligned}
\sin^2 2\theta_{23} &= 1.0 \\
\Delta m^2_{23} &= 2.2 \times 10^{-3} eV^2 \\
\chi^2/d.o.f. &= 119/126
\end{aligned}
$$

As a check of the DPAs for Water Cerenkov one can generate SuperK exposures and compare simulated results to published results.



Detector Configurations

1a,1b: Gadolinium in WC: no impact. WC photodetector coverage: Incorporate SK-I vs. SK-II efficiencies and resolutions, expect negligible impact.

2, 2a, 2b: 300’ impossible, 800’ need to know size of analysis fiducial volume. Background scaling based on numbers from Soudan 2 (2340 ft., had shield, measurements of cosmogenic backgrounds to atmos neutrinos)?

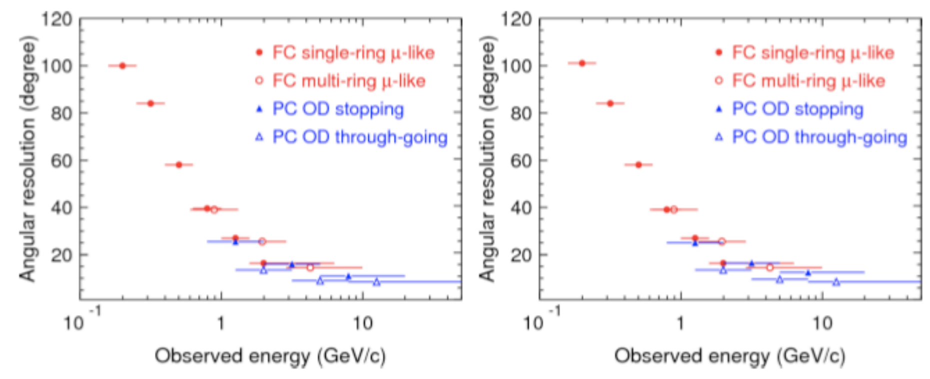


Figure 8.8: Angular resolution for SK1 (left) and SK2 (right).

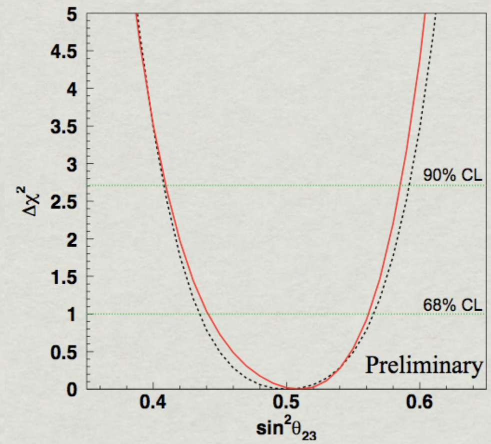
F. Dufour, Ph.D Thesis (2009)

3-6: Analysis use WC and Lar as separate bins in the fits.

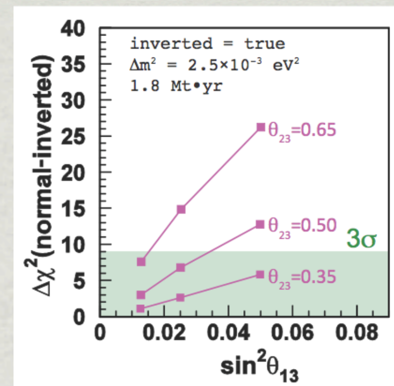
SENSITIVITIES

Plots are EXAMPLES

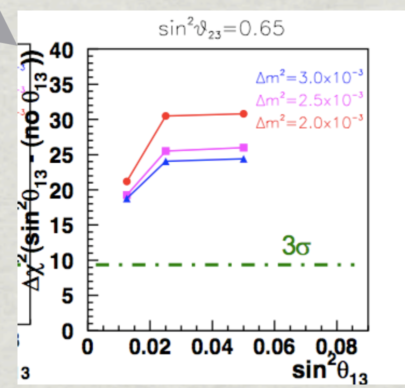
1: Determining octant of θ_{23}



2: Resolving the hierarchy as a function of true θ_{13}.



3: Measurement of θ_{13} as a function of true θ_{13}.



[2-3] each for (NH,IH), 3 x $\sin^2(\theta_{23})$

Have the tools but not the time:

- ★Precision on measurement of $\sin^2(2\theta_{23})$, Δm^2_{13}
- ★Sensitivity to exotic scenarios

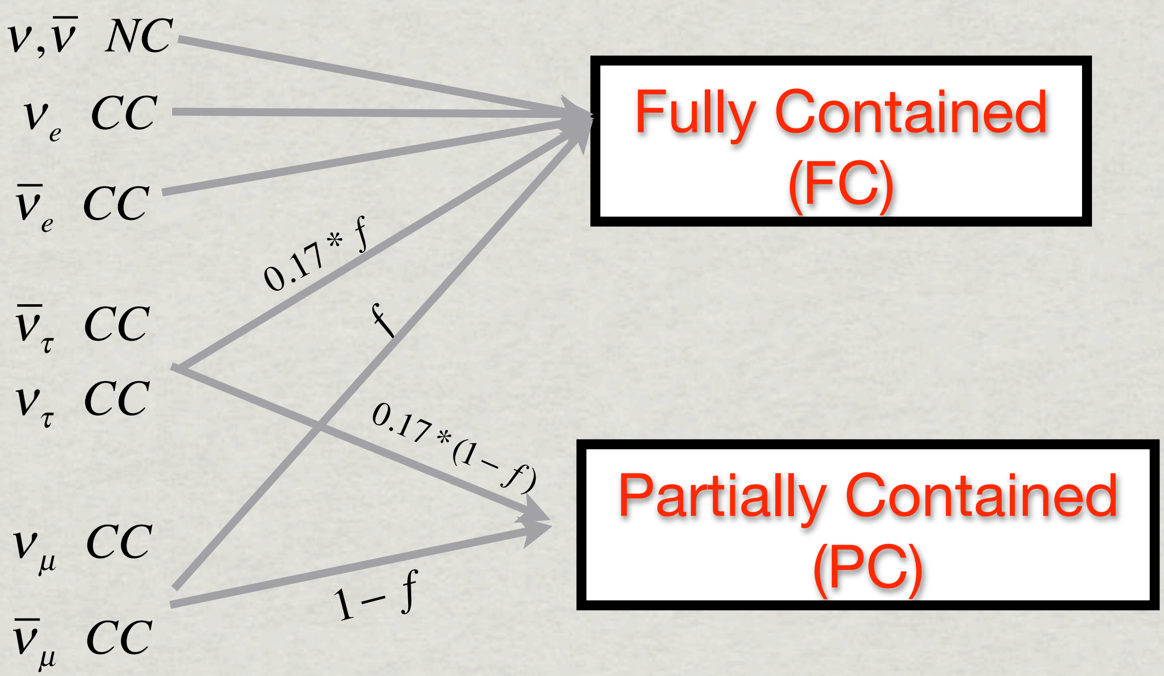
Don't have the tools:

- ★tau appearance (LAr 3.7σ in ICARUS studies)

LAr Detector Performance Assumptions

17 kt fid vol per module, zero background.

Categorization: ***containment, flavor, nu/nubar***



$f = f(E_\mu, \theta_\mu)$

is the containment probability for a muon track

(determined from detector geometry and fid. volume definition alone)

θ *(5GeV-E)*

LAr Detector Performance Assumptions

How are events *categorized*?

	$\nu_e - Like$		$\nu_\mu - Like$	$NC - Like$
$\nu_e \ CC \quad \bar{\nu}_e \ CC$	E_e>2 GeV	100%	0%	0%
	E_e<2 GeV	80%	0%	20%
$\nu_\mu \ CC \quad \bar{\nu}_\mu \ CC$	E_μ>2 GeV	0%	100%	0%
	E_μ<2 GeV	0%	81%	19%
$\nu_\tau \ CC \quad \bar{\nu}_\tau \ CC$		17%	17%	66%
$\nu, \bar{\nu} \ NC$		0%	8%	92%

Ref: Icarus, Bueno Neutrino 2004)

LAr Detector Performance Assumptions

Within the $\nu_e - Like$ and $\nu_\mu - Like$ samples separate out:

Assume 75% of stopping μ^- are captured on nucleus
100% of stopping μ^+ give Michel electron

Neutrino tag: muon track + p only in final state (QEL)
Antineutrino tag: muon track only in final state (QEL)
Antineutrino tag: decay electron from mu track (mu+ in FS)

Suggestion: A simple scan of mixed CC nu/nubar interactions at a handful of energies from 300 MeV to 10 GeV would be very helpful. How reliable is nu/nubar tagging?

DPAs - LAr

	reconstruction 'scheme'-v0	*reconstruction 'scheme' -v1*
DPA	LArV1	Better
Classification	See previous slides $f(E,\theta)=\theta(5\text{ GeV}-E)$	Realistic $f(E,\theta)$
Muon Energy	17% exiting [1] 6% contained [?]	Range E resolution?
EM shower energy	3%/sqrt(E) [2]	OK
Hadronic resolution	30%/sqrt(E) [2]	Single particle-based
ν angular resolution	10° [3]	Single particle-based

[1]: B. Fleming
[2]: ICARUS / Lar (Guglielmi, Neutrino 2010, A. Rubbia - hep-ph/0402110)
[3] Gandhi et al. arXiv:0807.2759 (2008)

LAr reconstruction

LAr atmospheric neutrino events would be reconstructed 'bubble-chamber' style.

Find and identify all particles, determine direction and energy. Neutrino direction is vector sum of individual particle momenta.

Particle	Detection Threshold	Energy resolution	Angular resolution
Muons	none	on previous	?
protons	none	[range]=?	?
charged pions	none	?	?
π^0	none	3%/sqrt(E)	?
neutrons	none	?	?

No smearing: Neutrino direction is taken from vector sum of particle momenta. These assumptions are equivalent to saying that in LAr pointing resolution for contained events is dominated by Fermi motion.

Simulation Tools

The LBNE atmospheric neutrino event driver is available in the latest version of GENIE *$GENIE/src/support/lbne.*

Generated several 100 kT-yrs of data for water and argon on the Tufts research cluster. Roughly 100 files, 30k events per file, one flavor only per file.

A new GENIE application to carry out simulated analysis. An AtNus library, 12 classes and 3 applications. *Will be documented and released as a general tool.*

AtNuReco: inputs assumptions about event Classification and reconstruction (resolutions, Classification dependent), outputs 'pseudo-reconstructed' events. (Each event is reconstructed as each neutrino flavor to incorporate oscillations later on).

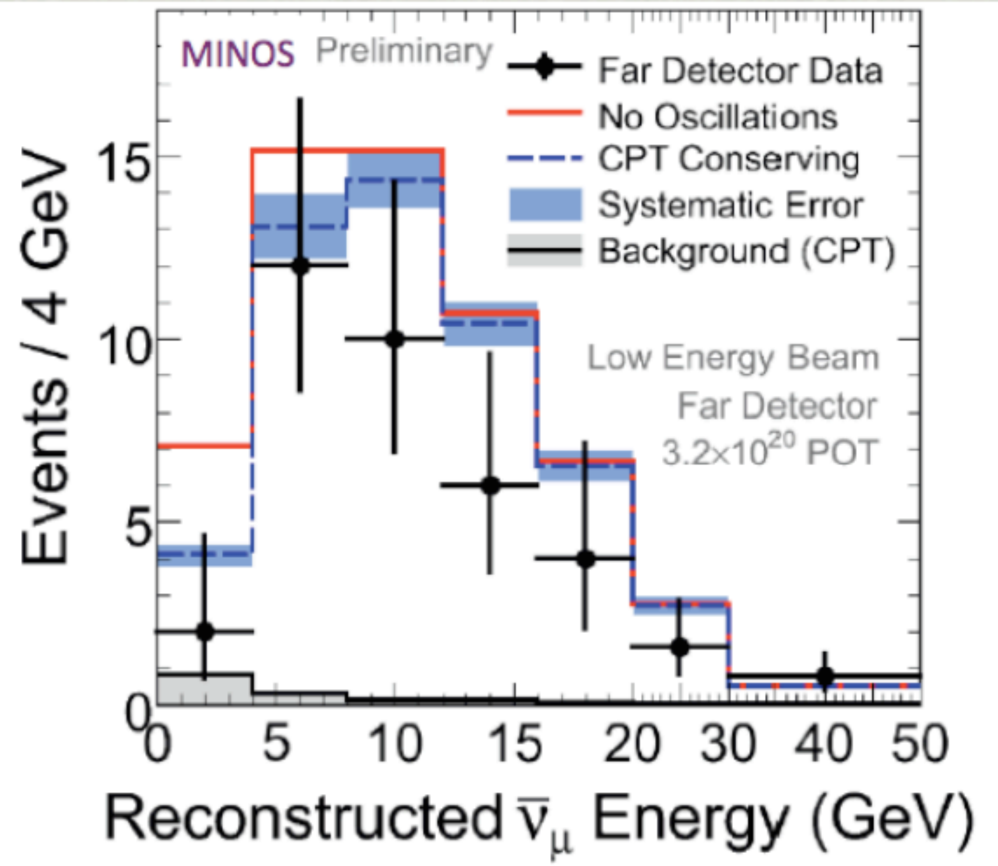
AtNuBinner: Inputs information about how the data will be binned (event categories, cuts, observables, bin sizes). Outputs for each event the minimum amount of information necessary to do a fit (a bin id for each event/flavor) and enough truth info to reweight the events (oscillations and systematics).

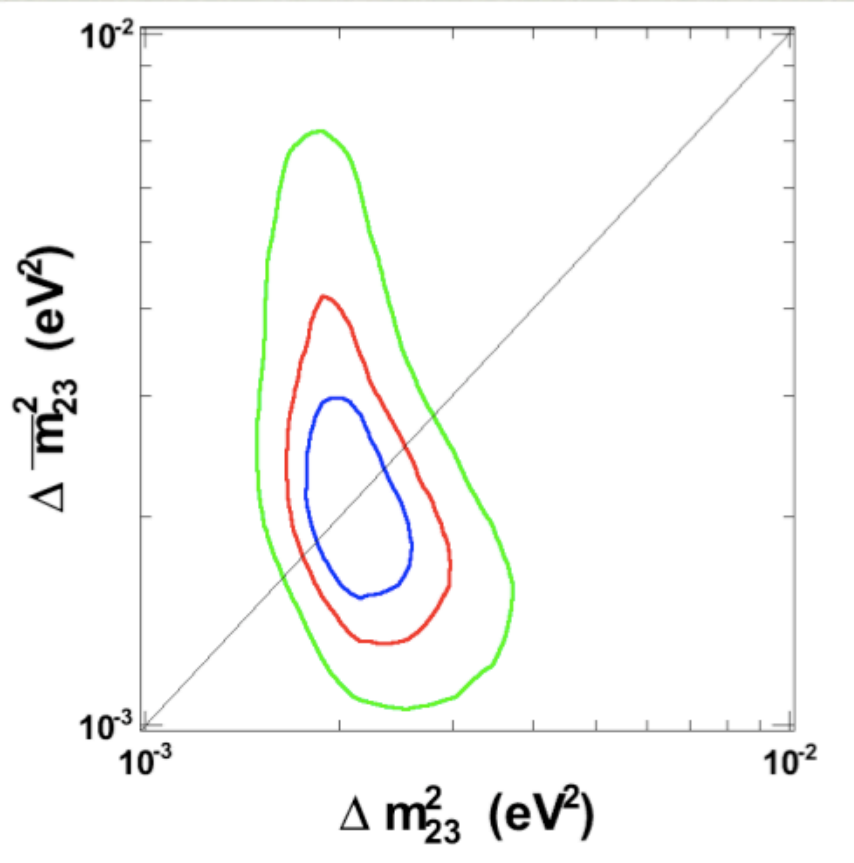
AtNuAnalysis: Reads in the AtNuMini objects, bins the data under different oscillation / systematic parameters and calculates statistical metrics.

CPT Violation?

MINOS can distinguish neutrinos from anti-neutrinos on an event-by-event basis by +/-charged particle discrimination.

Super-K must rely on statistical sensitivity from different fluxes, cross sections, etc.





Exotic Scenarios

Model	Exclusion level or limit
$\nu_\mu \rightarrow \nu_s$ oscillation	SK-I+II: 7.3σ
Admixture (2+2 hierarchy)	SK-I+II: 23% allowed
Decay I ($\sin^4\theta + \cos^4\theta\, e^{-\alpha L/E}$)	SK-I+II: 17σ
Decay II ($(\sin^2\theta + \cos^2\theta\, e^{-\alpha L/2E})^2$)	SK-I+II: 3.9σ
Decay Limit (GeV^2)	SK-I+II: 6.5×10^{-23}
Decoherence ($(1+e^{-\beta L/E})/2$)	SK-I+II: 4.2σ
Decoherence Limit (GeV)	SK-I+II: 6.0×10^{-24}
LIV Limit	SK-I+II: 1.2×10^{-24}
CPTV Limit (GeV)	SK-I+II: 0.9×10^{-23}
MaVaNs (various models)	SK-I: $3.5\text{-}3.8\sigma$
Non-Standard Interactions	Need number here

Neutrinos frequently set stringent limits, although not usually testing exactly the same parameters.

e.g., cosmic ray spectrum LIV $< 10^{-15}$, NMR LIV $< 10^{-22}$

K^0K^0bar CPTV $< 10^{-18}$

What have we already learned?

$$U = \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \boxed{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}} \boxed{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

$s_{ij} \equiv \sin\theta_{ij}$
$c_{ij} \equiv \cos\theta_{ij}$

Atmospheric Mixing Parameters

- Zenith angle analysis (Phys. Rev. D 74, 032002 (2006))
- Tau appearance (Phys. Rev. Lett. 97, 171801 (2006))
- L/E analysis (Phys. Rev. Lett. 93, 101801 (2004))
- Solar terms analysis (arXiv:1002.3471 [hep-ex] (2010))

Mass Hierarchy and Value of θ_{13}

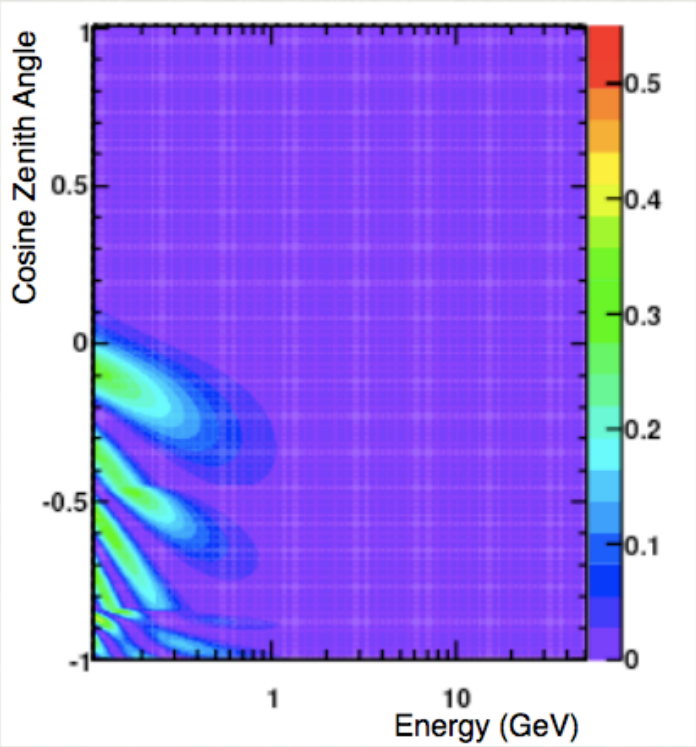
- 3-flavor zenith angle analysis (arXiv:1002.3471 [hep-ex] (2010))

And other scenarios:

MaVaNs (Phys. Rev. D 77, 052001 (2008))
Exotic scenarios: LIV, CPT, Sterile (W. Wang PhD Thesis (2007))
Non-standard interactions (G. Mitsuka PhD Thesis (2009))

Sub-dominant effects: θ_{23} Octant Degeneracy

Look for changes in low energy ν_e flux induced by solar-sector oscillations, assuming $\theta_{13} = 0$.



Driven by Δm^2_{12} and θ_{12}.

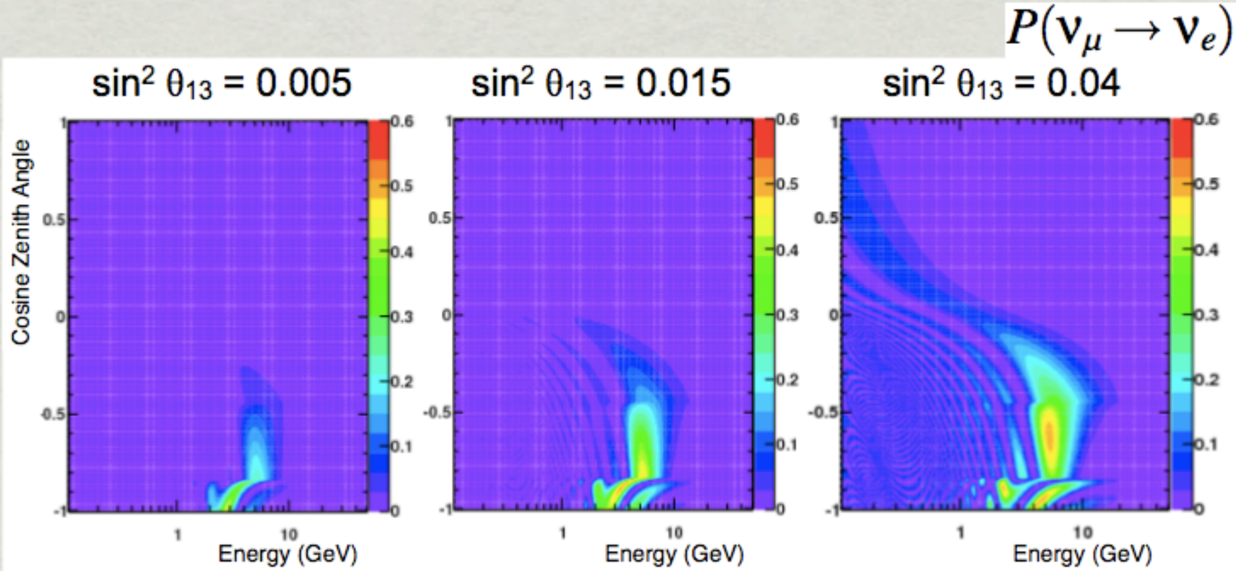
In constant density matter:

$$P\left(\nu_e \leftrightarrow \nu_\mu\right) = \cos^2\theta_{23}\, P\left(\nu_e \rightarrow \nu_x\right)$$

$$\begin{array}{lcll} \cos^2\theta_{23} & < & 0.5 & \nu_e \text{ flux reduction} \\ \cos^2\theta_{23} & = & 0.5 & \\ \cos^2\theta_{23} & > & 0.5 & \nu_e \text{ flux enhancement} \end{array}$$

Try to determine octant of θ_{23} by observing changes in the flux of low energy e-like samples.

Sub-dominant effects: non-zero θ_{13} & mass hierarchy



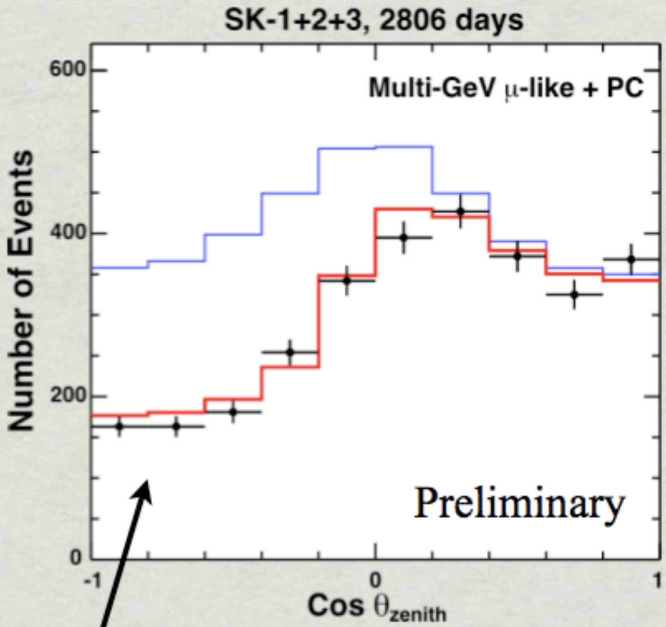
MSW effect gives rise to additional scattering amplitudes in matter (for ν_e only).

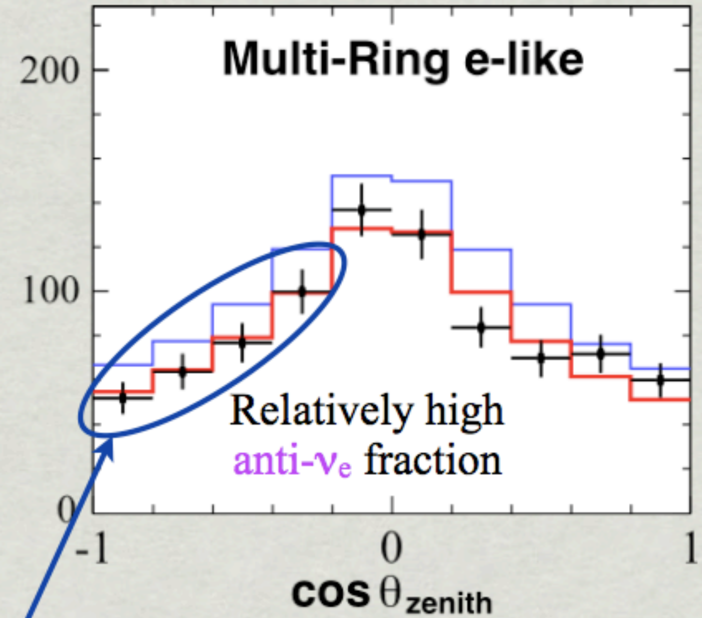
Clearest indication of non-zero θ_{13} at SK:
resonance @ ~2-10 GeV for up-going e-like events

Normal hierarchy $\Rightarrow$ neutrino enhancement

Inverted hierarchy $\Rightarrow$ anti-neutrino enhancement

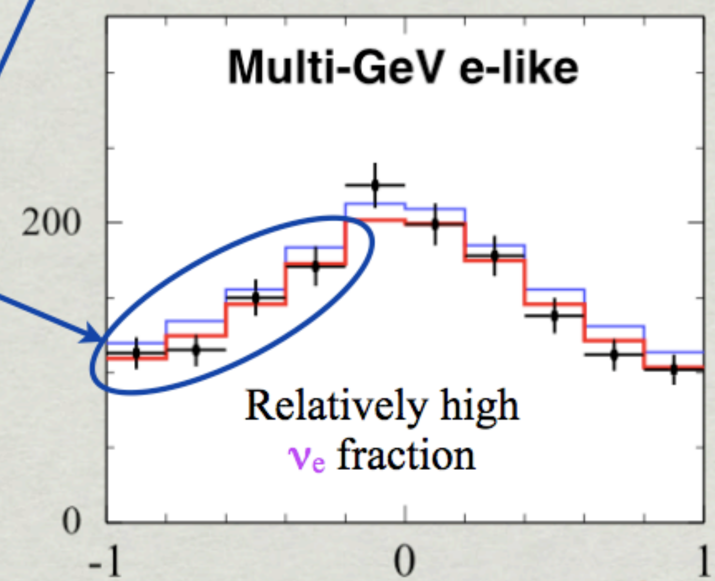
Analysis uses 3 parameters ($\sin^2\theta_{13}$, $\sin^2\theta_{23}$, Δm^2_{23}) assuming a single "dominant mass scale" ($\Delta m^2_{23} \gg \Delta m^2_{12}$).



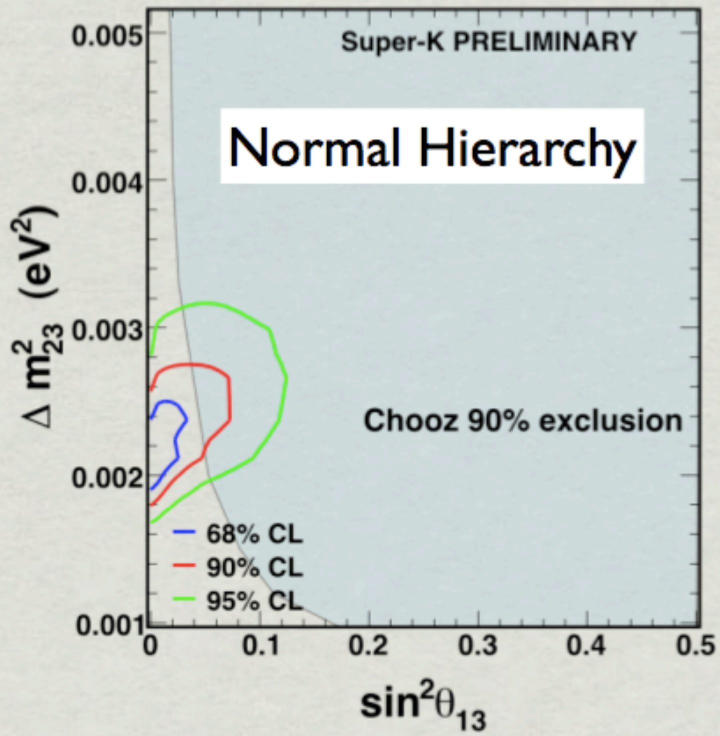


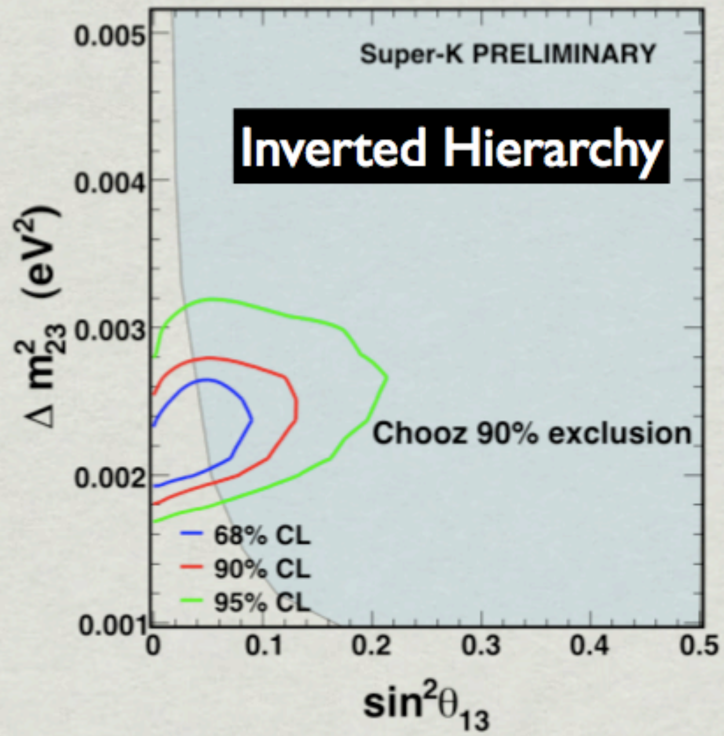
Clear distortion of muon-like zenith distribution, well-described by 2-flavor $\nu_\mu \rightarrow \nu_\tau$ disappearance...

Allow also $\nu_\mu \rightarrow \nu_e$ appearance in 3-flavor analysis, look for enhancement of high-energy upward-going e-like events.



No distortion in electron-like samples...
no evidence for matter-enhanced ν_e appearance.

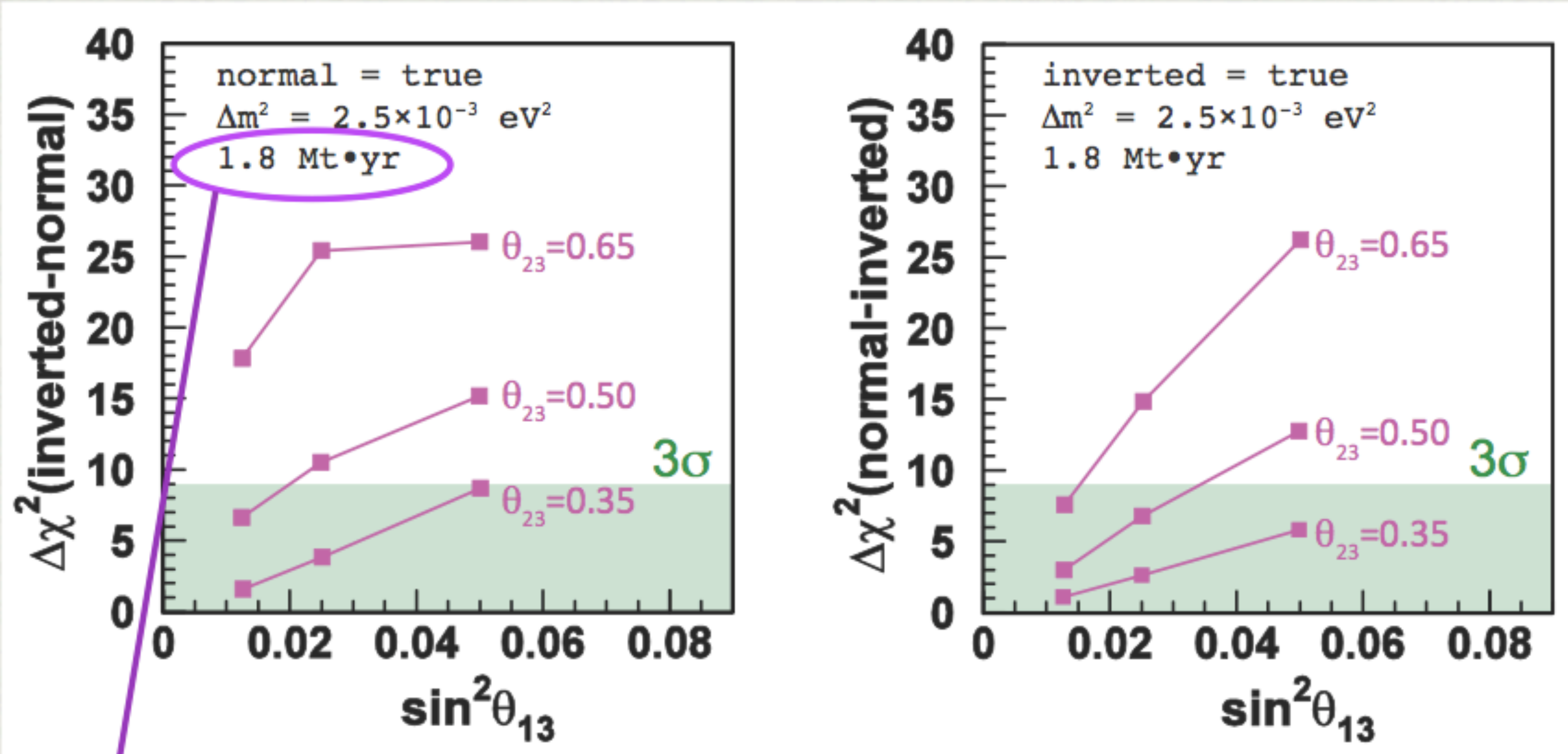




	χ^2/dof	Δm^2_{23}	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$
Normal	469/417	2.1×10^{-3}	0.50	0
Inverted	468/417	2.1×10^{-3}	0.55	0.01

Data consistent with both hierarchies; no electron-like excess observed.
Analysis assumes $\Delta m^2_{12} = 0$, next update will include solar terms.

Sensitivity to Mass Hierarchy

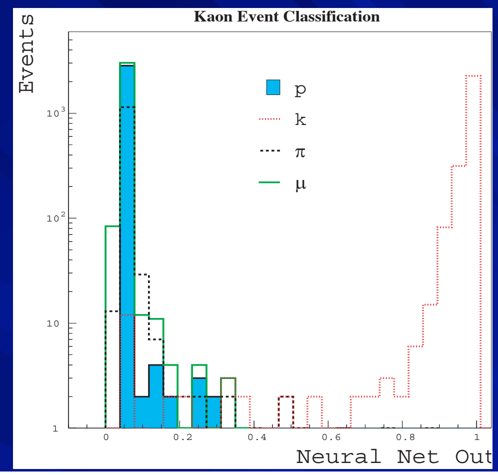


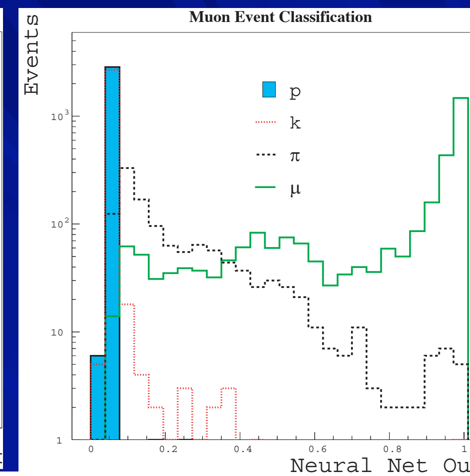
Smaller detector volume requires longer measurement time.

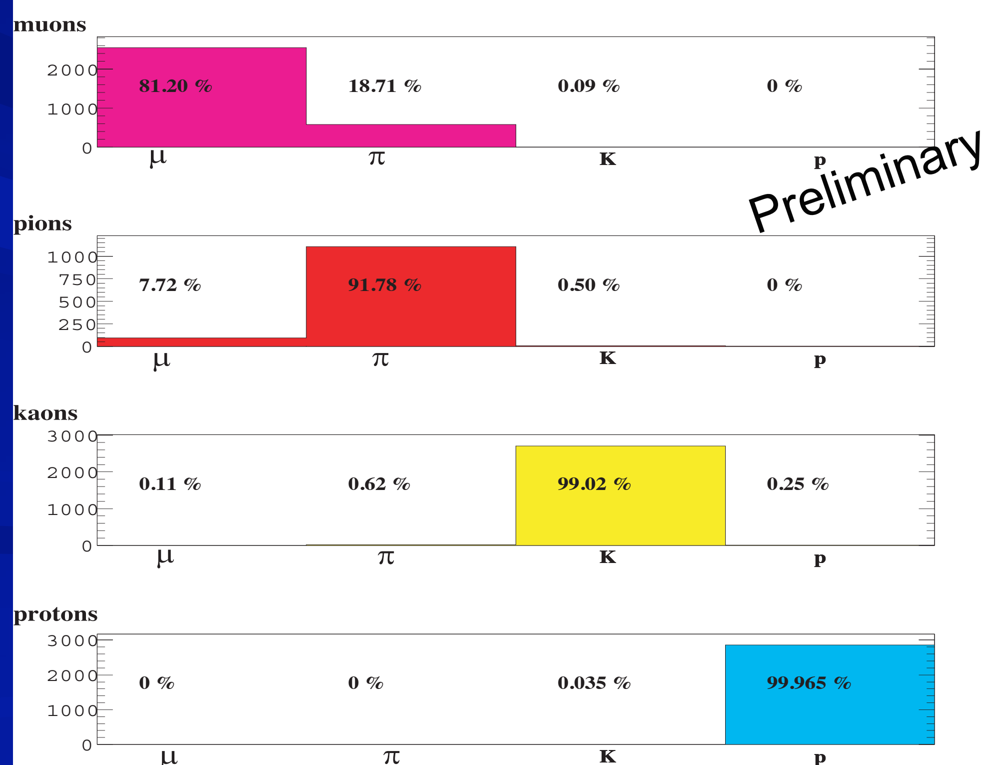
A. Bueno, ICARUS
Neutrino 2004

Identification: Neural Network

- Full generation and 3D reconstruction of muons, pions, protons and kaons
- Analysis based on neural network. Discrimination given by:
  - Different stopping power for each particle type
  - Difference on secondary particle production after decay/interaction of parent track
  - Key issues:
    - Accurate energy measurement
    - Good spatial resolution for precise tracking reconstruction
- Very high identification efficiencies (>90%) while low contamination levels (few %) are expected







Other LAr Questions

This analysis ignores upgoing-stopping and upward-throughgoing. Can these be identified and over what range of zenith angle?

Should one include a tau-like category?

Muon containment fraction $f = f(E_\mu, \theta_\mu)$

Energy resolution and detection thresholds for contained particles (assumed here to be perfect).

Other suggestions for separating neutrinos and anti-neutrinos at higher energies?

Better numbers, energy dependence for the event identification Table?

Liquid Argon

Sources of information - LAr data and previous simulation studies:

Bonnie (energy resolutions, containment questions) - Thanks!

ICARUS

A. Guglielmi, Neutrino 2010

RESOLUTIONS

Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(\mathrm{MeV})} + 2\%$

Electromagn. showers: $\sigma(E)/E = 3\% / \sqrt{E(\mathrm{GeV})}$

Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(\mathrm{GeV})}$

GLACIER (***Large underground, liquid based detectors for astro-particle physics in Europe: scientific case and prospects, D. Autiero et al, JCAP11(2007)011.***)

R. Gandhi et al., arXiv-0807.2759 (2008).

Electron energy: 3%/sqrt(E)

muon energy: 15%

hadronic energy 30%/sqrt(E)

Angular resolution: neutrino direction 10^o

Zenith Angle Analysis

Data binned according to:

event type + momentum + zenith angle } 420 bins for SK-I, 420 bins for SK-II, 420 bins for SK-III

Datasets	
SK-I FC/PC:	1489 days
SK-I Upmu:	1646 days
SK-II FC/PC:	798 days
SK-II Upmu:	828 days
SK-III FC/PC:	518 days
SK-III Upmu:	635 days

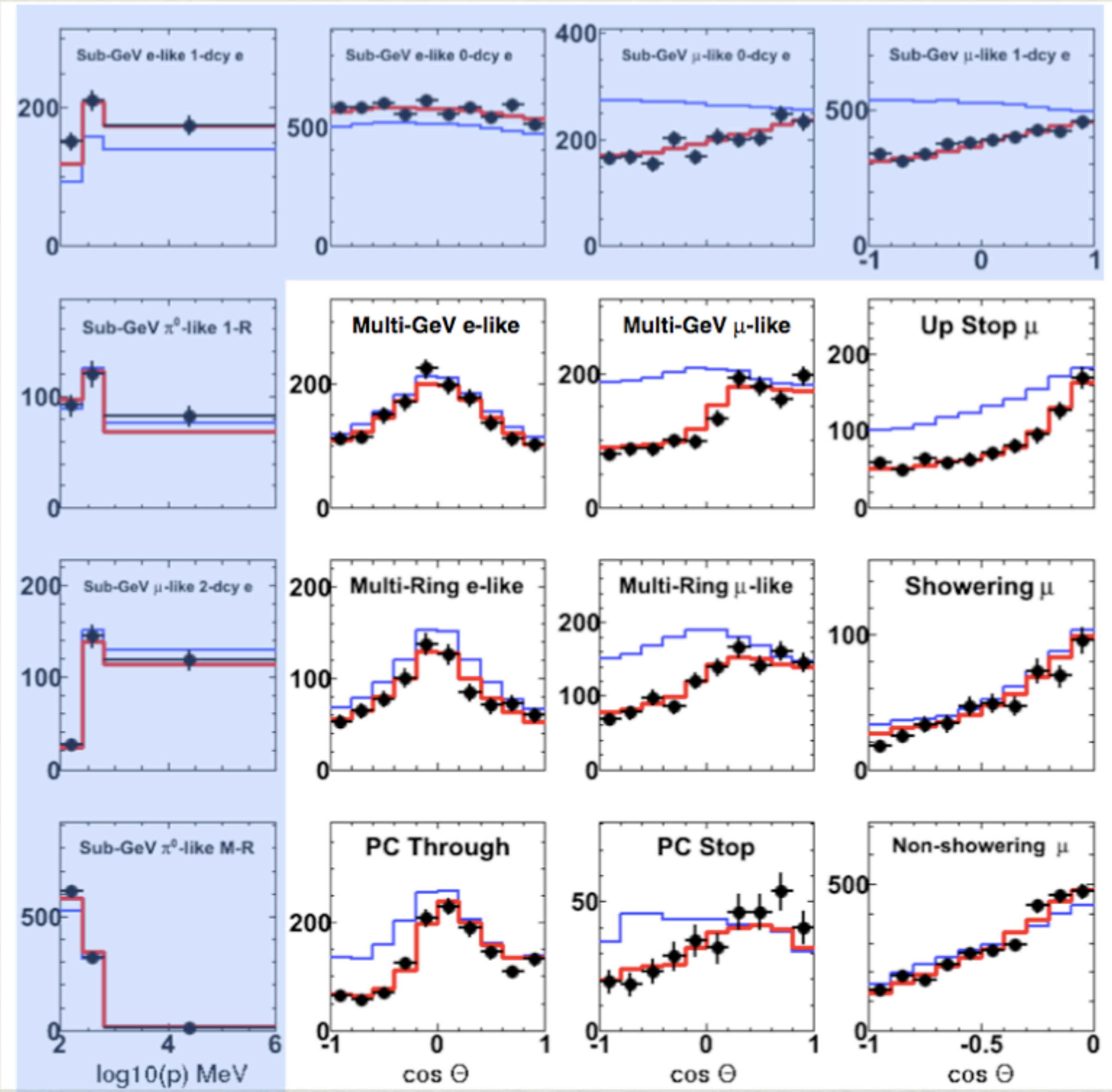
χ^2 fit in bins of zenith angle with systematic error pull terms:

$$\chi^2 = \sum_{i=1}^{N_{bins}} 2\left(N_i^{exp} - N_i^{obs} + N_i^{obs} \ln \frac{N_i^{obs}}{N_i^{exp}}\right) + \sum_{j=1}^{N_{sys}} \left(\frac{\varepsilon_j}{\sigma_j^{sys}}\right)^2$$

where $$N_i^{exp} = N_i^0 \cdot P\left(\nu_\alpha \to \nu_\beta\right)\left(1 + \sum_{j=1}^{N_{sys}} f_j^i \varepsilon_j\right)$$

122 systematic error terms to account for uncertainties in:

- Neutrino flux
- Cross sections
- Event reconstruction
- Data reduction



Sub-GeV samples subdivided to improve sensitivity to low energy oscillation effects

- Data
- MC (no oscillations)
- MC (best fit oscillations)

Quantity	LBL	Atmos	Atmos - Lar
$\sin^2(2\theta_{13})$ (3σ)	$3\mathrm{x}10^{-3}$ δ=0, NH 1500 kt-yr WC Ref: PWGIReport_V0.3	$48\mathrm{x}10^{-3}$ (depends strongly on $\sin^2(\theta_{23})$) allowed region goes as ~(exposure) SK 20 yrs (450 kt-yr) Ref: KajitaNOON24	
$\sin^2(2\theta_{23})$	.005 (68% CL) 1500 kton-yrs LAr Ref: PWGIReport_V0.3 Fig. 11	.05 (90%) SK20 years (450 kton-yr) Allowed region goes as sqrt(exposure) Ref: Kajita-NOON2004	
Δm^2_{23}	$.01 \times 10^{-3}$ eV^2 (1 σ CL) 1500 kton-yrs LAr Ref: PWGIReport_V0.3 Fig. 11	$.25 \times 10^{-3}$ eV^2 (90%) SK20 years (450 kton-yr) Allowed region goes as sqrt(exposure) Ref: Kajita-NOON2004	
Hierarchy			Resolved at (2σ) for $\sin^2(2\theta_{13}) > 40 \times 10^{-3}$ 333 kt-yr Ref: Gandhi hep-ph/0807.2759

A Dream Detector

Our dream detector:

Big!

Good flavor separation down to few hundred MeV.

Good neutrino energy and direction resolution.

Ability to distinguish neutrinos from anti-neutrinos.

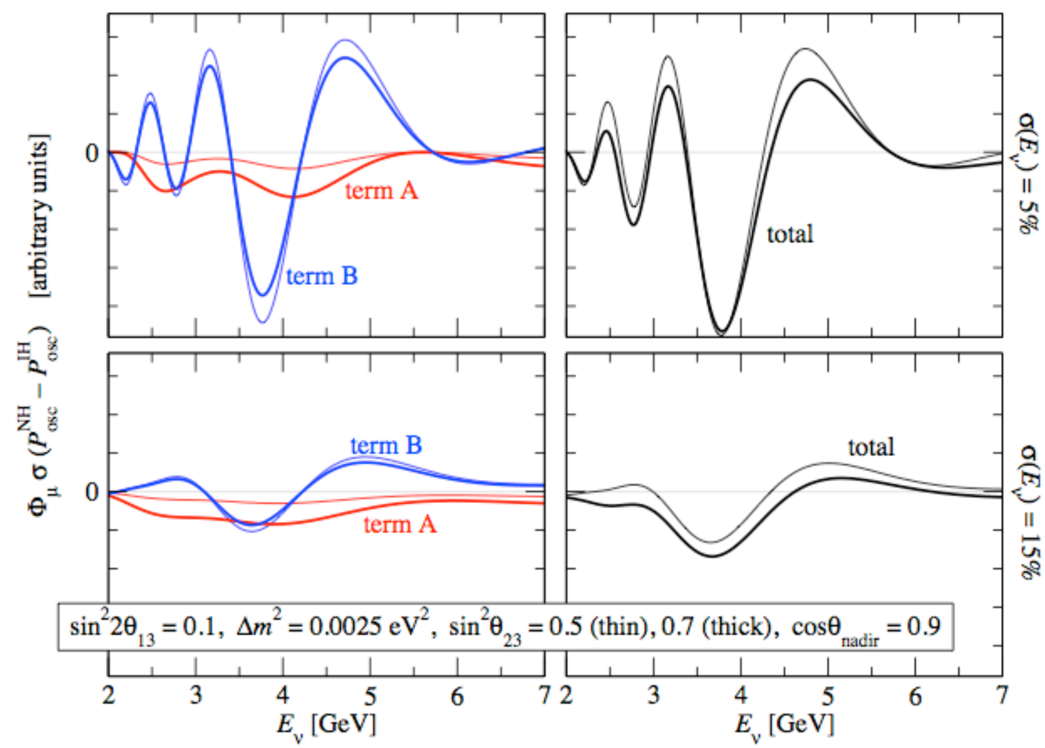


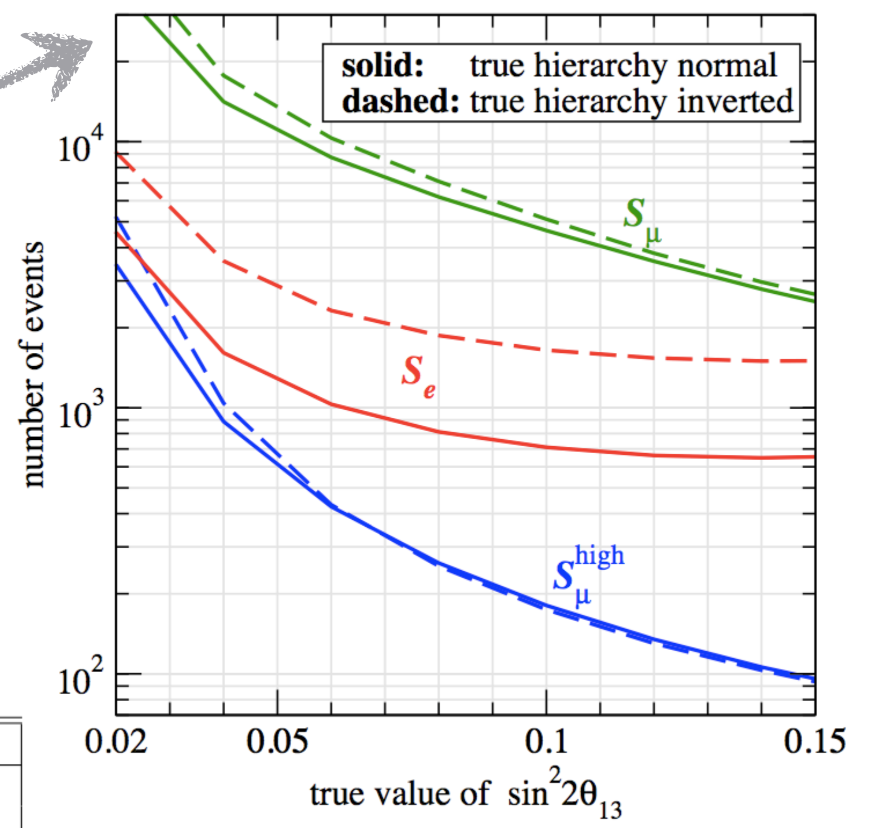
Figure 1: The difference between the μ-like event energy spectra corresponding to $\Delta m^2 > 0$ (NH) and $\Delta m^2 < 0$ (IH), ΔS^ν_μ, defined in Eq. (32). In the left panels terms A and B are displayed separately, in the right panels the total effect is shown. In the upper (lower) panels an energy resolution of 5% (15%) is taken into account. The Nadir angle is fixed to $\cos\theta_n = 0.9$ (no smearing included). Thin (thick) curves correspond to $\sin^2\theta_{23} = 0.5\,(0.7)$.

"Determining the Neutrino Mass Hierarchy with Atmospheric Neutrinos", Petcov and Schwetz, hep-ph/0511277.

Towards a Dream Detector

Number of events required to resolve the hierarchy at 2σ.

For best measurements, one wants to observe features in the oscillogram - which requires excellent energy and angular resolution or signals are washed out.

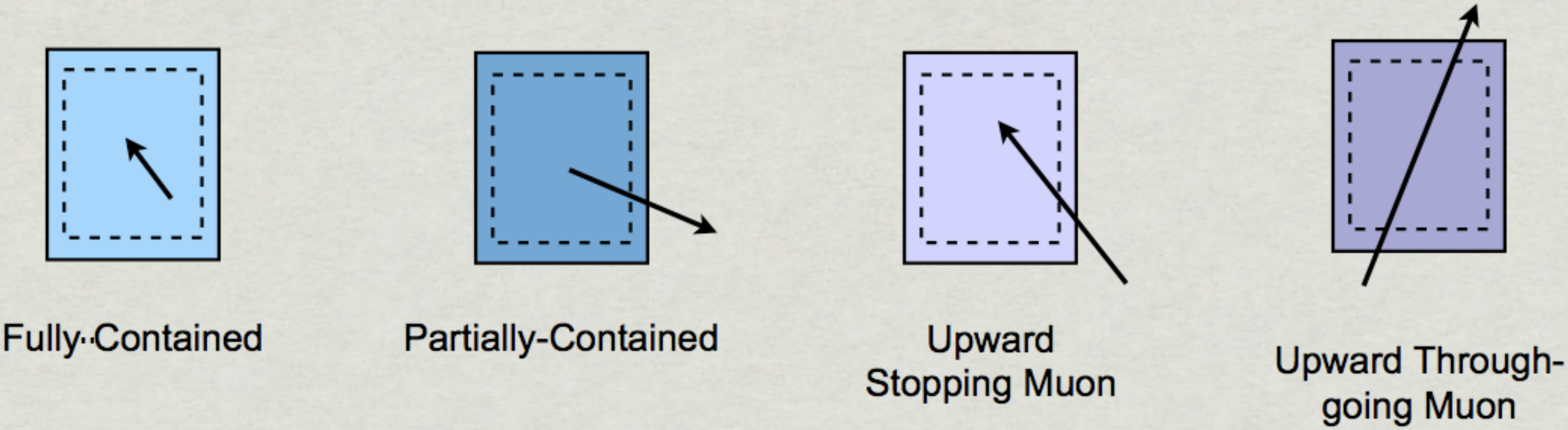


setup label	S_μ^{high}	S_μ	S_e
event type	μ-like	μ-like	e-like
energy range	$2\text{ GeV} \leq E_\nu \leq 10\text{ GeV}$		
Nadir angle range	$0.1 \leq \cos\theta_n \leq 1$		
number of bins in $E_\nu \times \cos\theta_n$	20×20	20×20	20×20
charge identification	95%	95%	80%
systematical errors	included according Tab. 1		
energy resolution σ_E	5%	15%	15%
angular resolution σ_{dir}	5°	15°	15°

"Determining the Neutrino Mass Hierarchy with Atmospheric Neutrinos", Petcov and Schwetz, hep-ph/0511277.

What are the data samples?

Event Categories



	Fully Contained	Partially Contained	Upward Stopping Muon	Upward Through-going Muon
Mean E_ν	~1 GeV	~10 GeV	~10 GeV	~100 GeV
Energy range	100 MeV - 10 GeV	1 GeV - 100 GeV	1 GeV - 1 TeV	3 GeV - 100 TeV
Baseline	~10-13,000 km	~10-13,000 km	~500-13,000 km	~500-13,000 km